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(Werner-Heisenberg-Institut)

The AWAKE Plasma-Wakefield Experiment at CERN

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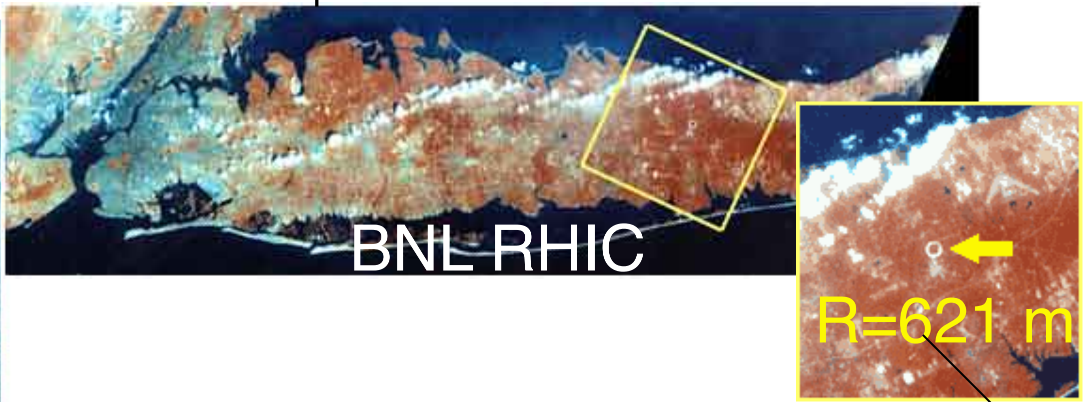
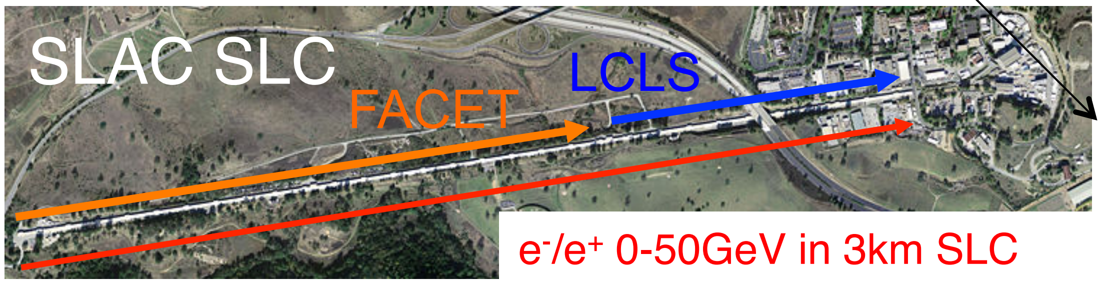
PARTICLE ACCELERATORS

AWAKE

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-23GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use rf technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

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AWAKE

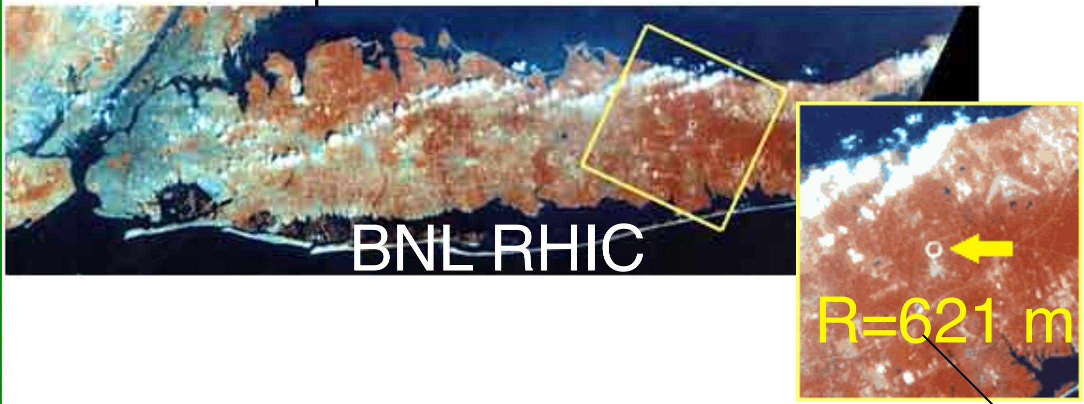
Light particles (e⁻/e⁺) accelerator
Limited by synchrotron radiation

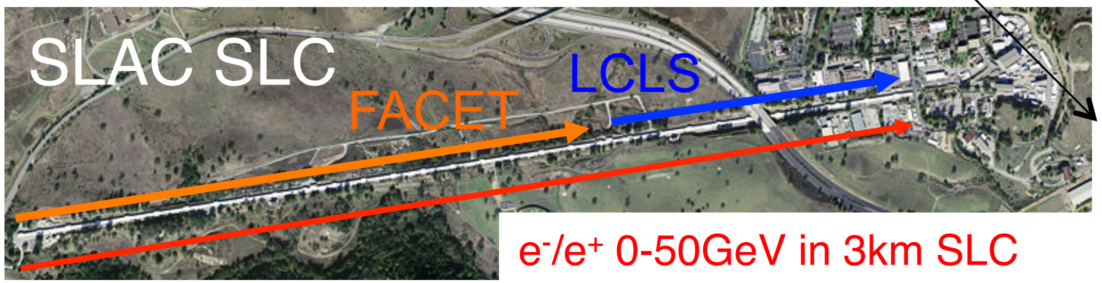
$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7}\frac{E^4}{R^2 m^4}$$

Must be linear
But …

↘ $$L = \frac{E(eV)}{G(eV/m)}$$ ↗

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





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… ate particles

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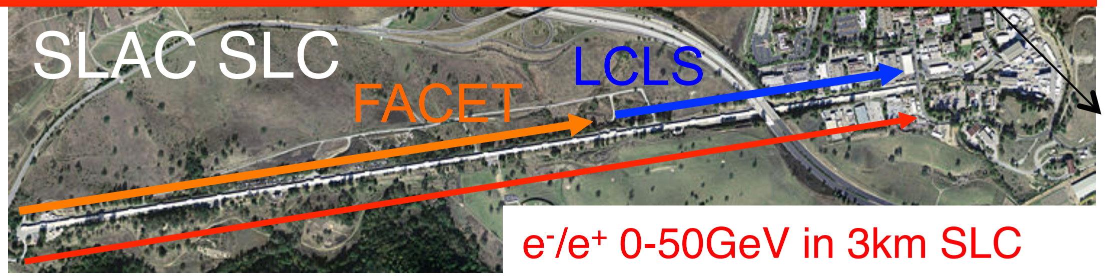
PARTICLE ACCELERATORS

AWAKE

Could plasmas be used to accelerate particles at high-gradient (>100MeV/m) and reduce the size and cost of a future linear e^-/e^+ collider or of a x-ray FEL?



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- Some of the largest and most complex (and most expensive) scientific instruments ever built!
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OUTLINE

- Introduction to Plasma Wakefield Accelerator (PWFA)
- Introduction to the self-modulation instability (SMI)
- SMI PWFA experiments at CERN with p^+: AWAKE
- SMI experiments at SLAC E209 with e^-/e^+
- Linear PWFA – SMI seeding at BNL-ATF
- Summary

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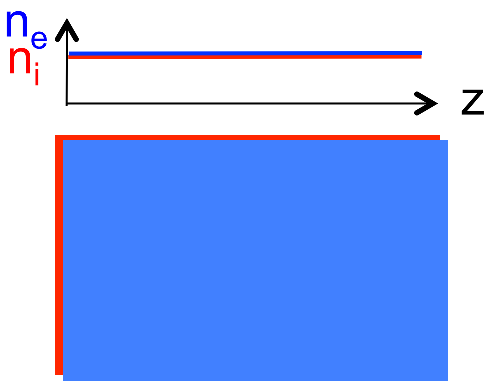
WHY PLASMAS?

✧Relativistic Electron Electrostatic Plasma Wave (Electrostatic, E_z//k):

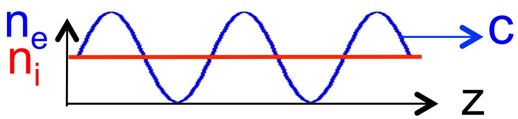


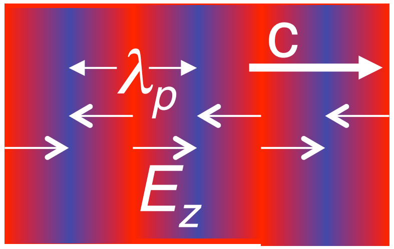
✧Plasmas wave or wake can be driven by:

- Intense laser pulses (LWFA)
- Dense particle bunch (PWFA)

WHY PLASMAS?

✧Relativistic Electron Electrostatic Plasma Wave (Electrostatic, E_z//k):





LARGE
Collective response!

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\varepsilon_0} \qquad k_p E_z=\frac{\omega_{pe}}{c}E_z=\frac{n_e e}{\varepsilon_0}$$

$$\omega_{pe}=\left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \text{ Plasma Frequency}$$

$$E_z=\left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e\left(cm^{-3}\right)}=1\,GV/m$$

$n_e=10^{14}$ cm^{-3}

Cold Plasma "Wavebreaking" Field

$$E_{WB}=m_e c\,\omega_{pe}/e$$

✧Plasmas can sustain very large (collective) E_z-field, acceleration

✧Wave, wake phase velocity = driver velocity (~c when relativistic)

✧Plasma is already (partially) ionized, difficult to "break-down"

✧Plasmas wave or wake can be driven by:

➢Intense laser pulses (LWFA)
➢Dense particle bunch (PWFA)

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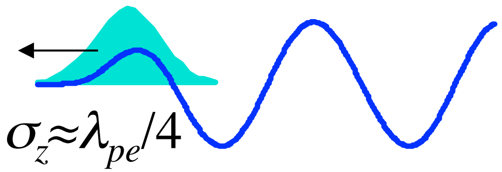
4 PLASMA ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

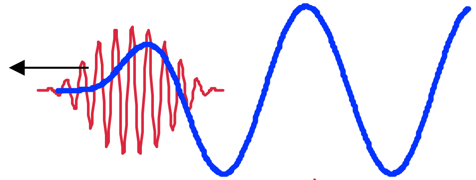
  A high energy particle bunch (e^-, e^+, ...)

  P. Chen et al., Phys. Rev. Lett. 54, 693 (1985)



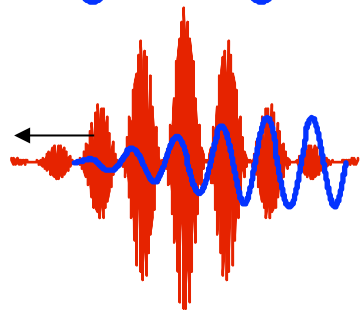
- Laser Wakefield Accelerator (LWFA) *

  A short laser pulse (photons, ponderomotive)



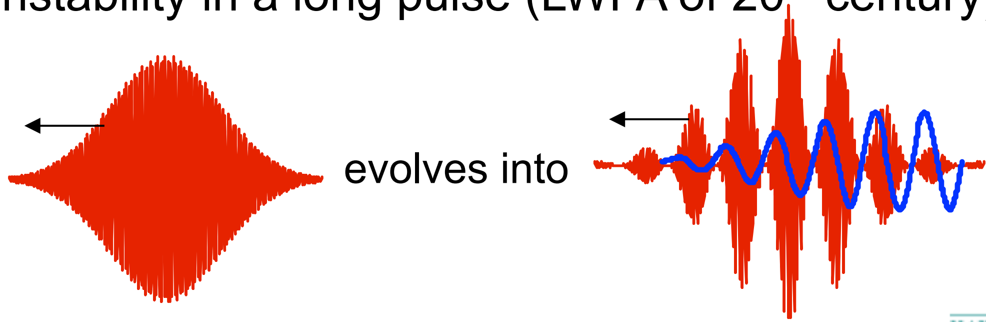
- Plasma Beat Wave Accelerator (PBWA) *

  Two frequencies laser pulse, i.e., a train of pulses



- Self-Modulated Laser Wakefield Accelerator (SMLWFA) *

  Raman forward scattering instability in a long pulse (LWFA of 20th century)



*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

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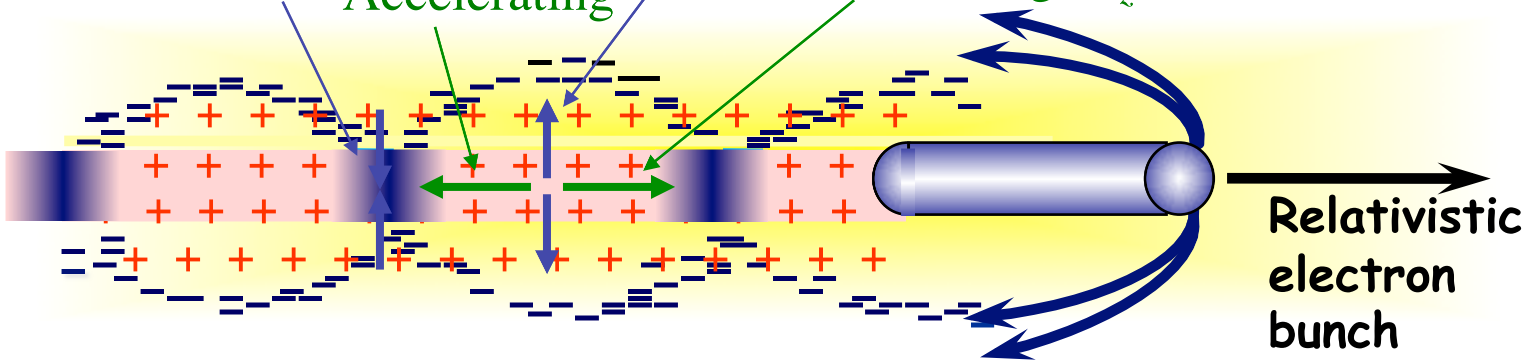
PLASMA WAKEFIELD ACCELERATOR (e^-)

AWAKE



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge force => deceleration + focusing (MT/m)
- Plasma e^- rush back on axis => acceleration, GV/m
- Ultra-relativistic driver => ultra-relativistic wake
  => no dephasing
- Particle bunches have long "Rayleigh length"
  (beta function $\beta^*=\sigma^{*2}/\varepsilon$~cm, m)
- Acceleration physics identical PWFA, LWFA

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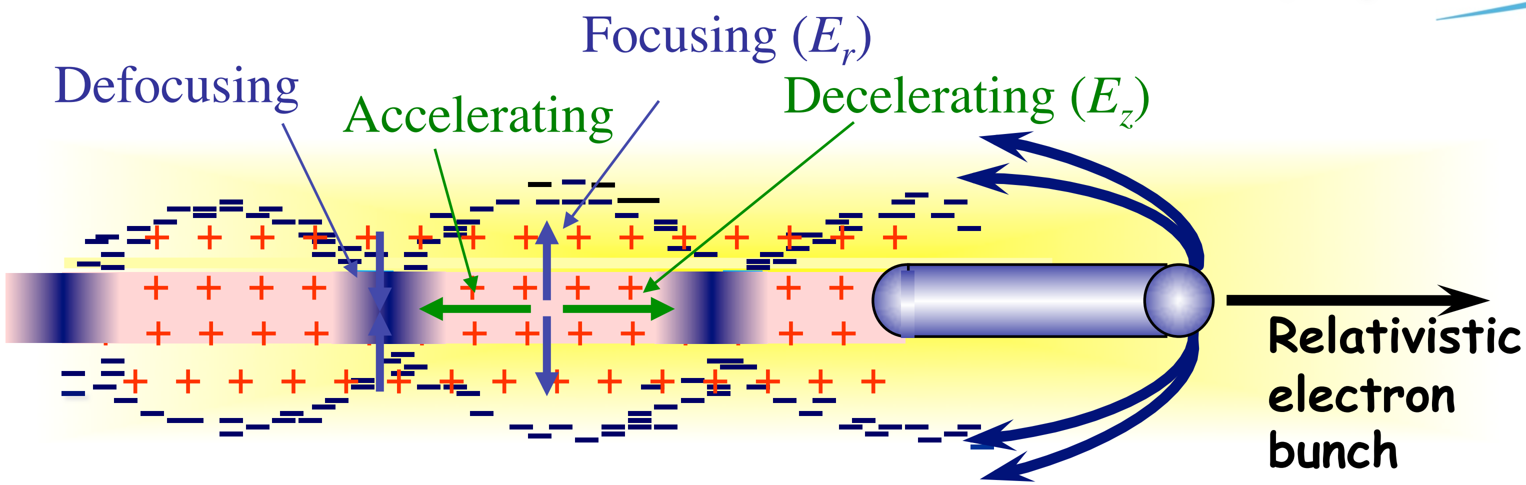
PLASMA WAKEFIELD ACCELERATOR (e^-)



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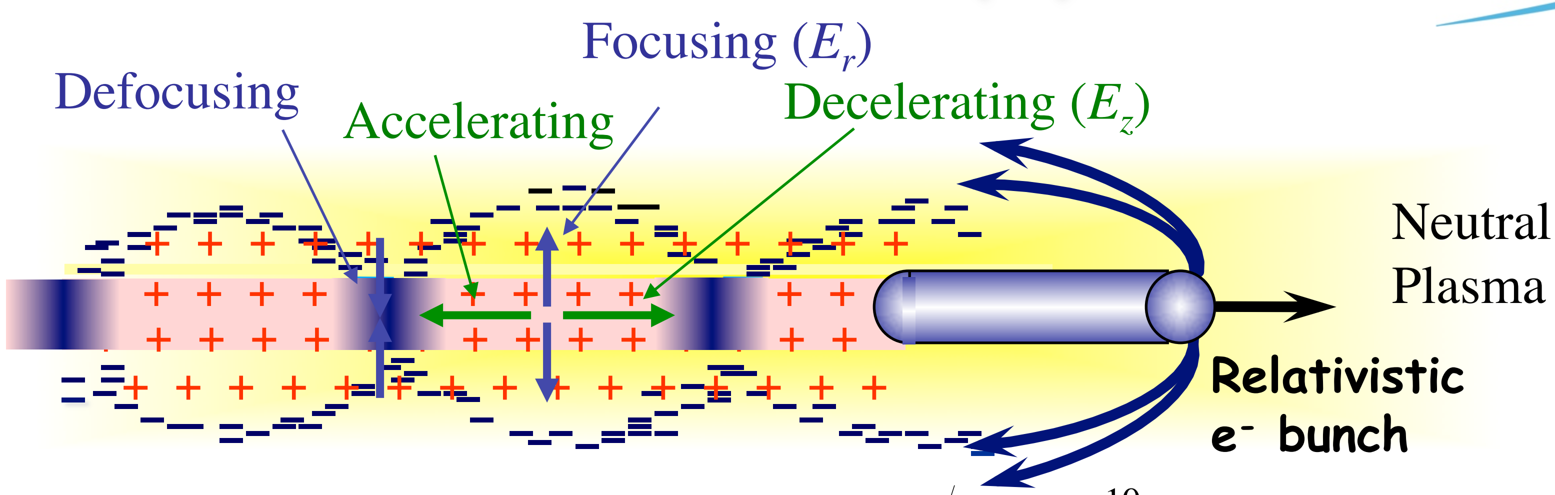
- …ver => ultra-relativistic wake
  => no dephasing
- …ave long Rayleigh lengths”
  …^{2}/ε~cm, m)
- Acceleration physics identical PWFA, LWFA

Very large energy gain possible with short, high-energy relativistic bunches!

PWFA Numbers (e^-)



✧Linear theory (n_b<<n_e) scaling:

$$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2} \approx N/\sigma_z^2$$

$$@\ k_{pe}\sigma_z \approx \sqrt{2}\ (with\ k_{pe}\sigma_r <<1)$$

✧Focusing strength: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c}$ (n_b>n_e)

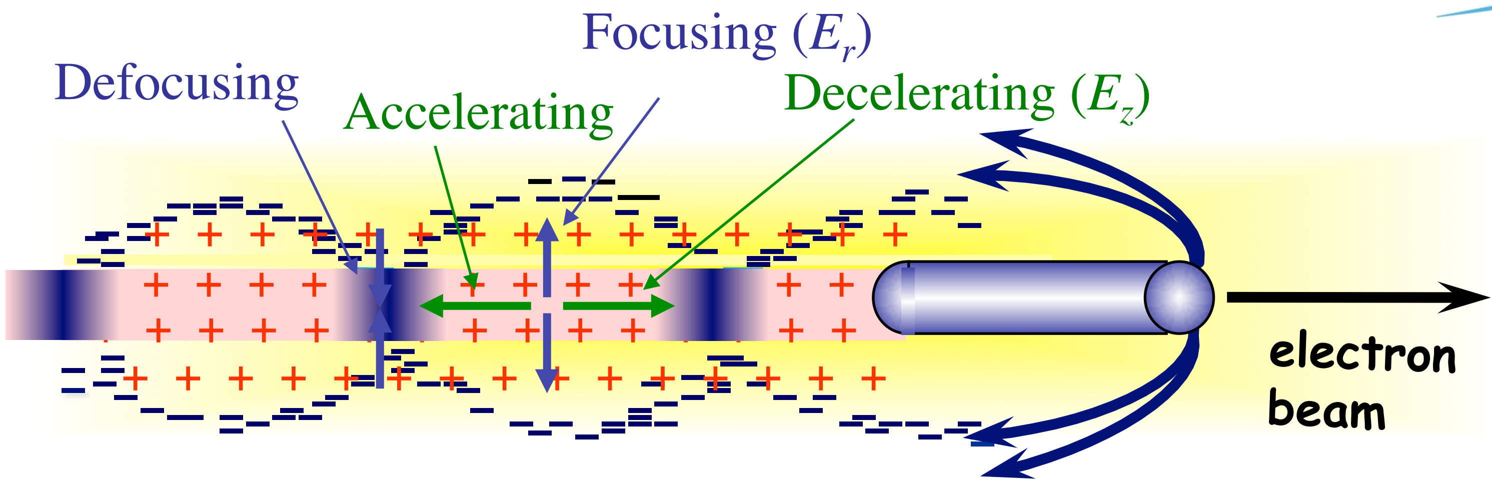
✧$N=2\times10^{10}$: σ_z=600 μm, $n_e=2\times10^{14}$ cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m

σ_z= 20 μm, $n_e=2\times10^{17}$ cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

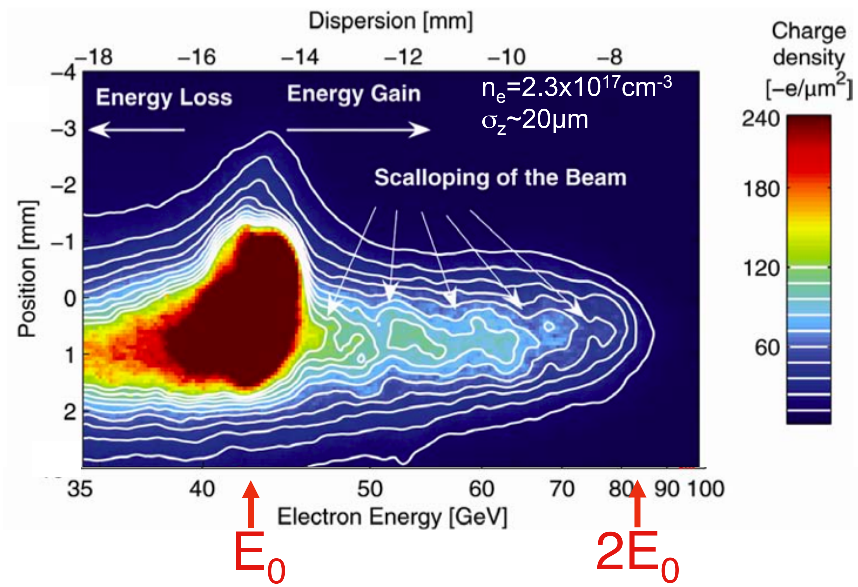
✧Frequency: 100GHz to >1THz, "structure" size 1mm to 100μm

✧Conventional accelerators: MHz-GHz, E_{acc}<150 MV/m, B_θ/r<2 kT/m

PLASMA WAKEFIELD ACCELERATOR (e⁻)



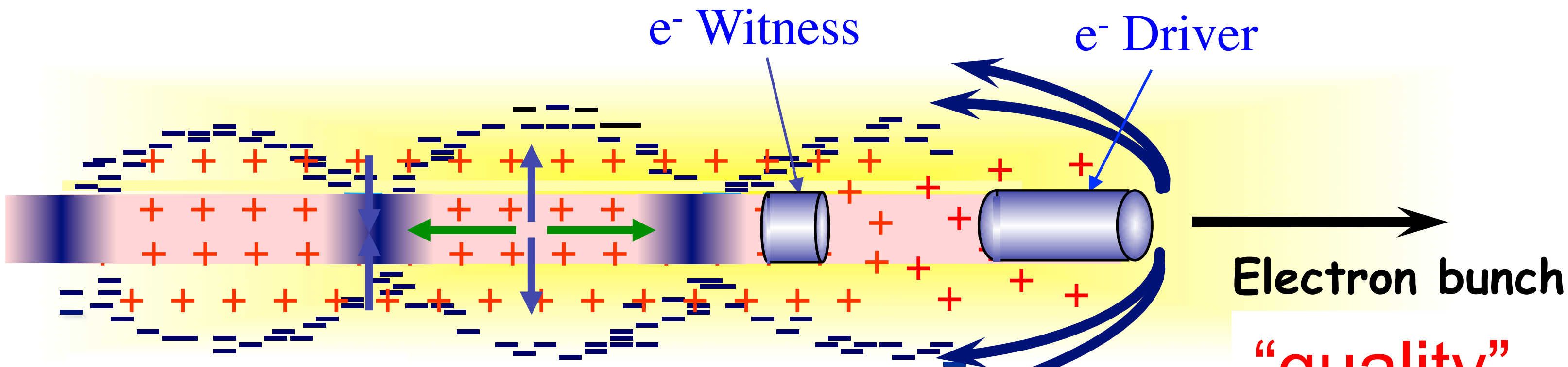
Blumenfeld, Nature 445, 741 (2007)



42 => 84GeV in 85cm! 50GeV/m

Muggli, Phys. Rev. Lett. 93, 014802 (2004)
Hogan, Phys. Rev. Lett. 95, 054802 (2005)
Muggli, Hogan, Comptes Rendus Physique, 10 (2-3), 116 (2009)
Muggli, New J. Phys. 12, 045022 (2010)

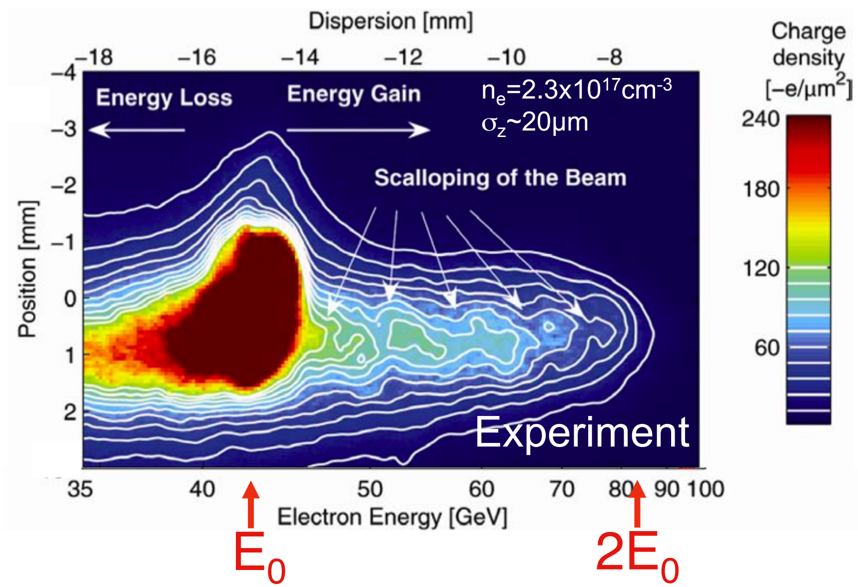
PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)

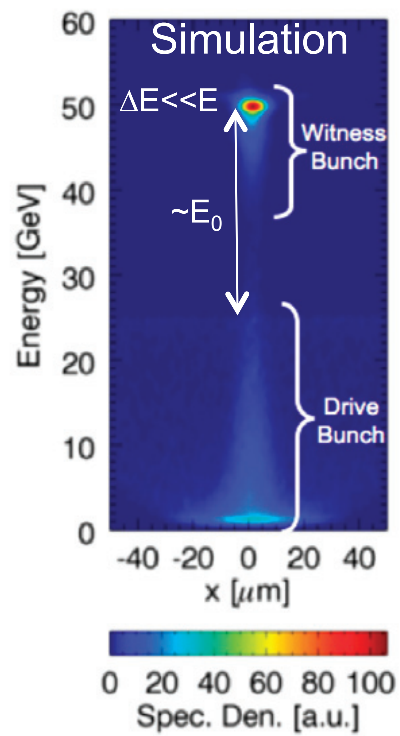


42 => 84GeV in 85cm! 50GeV/m

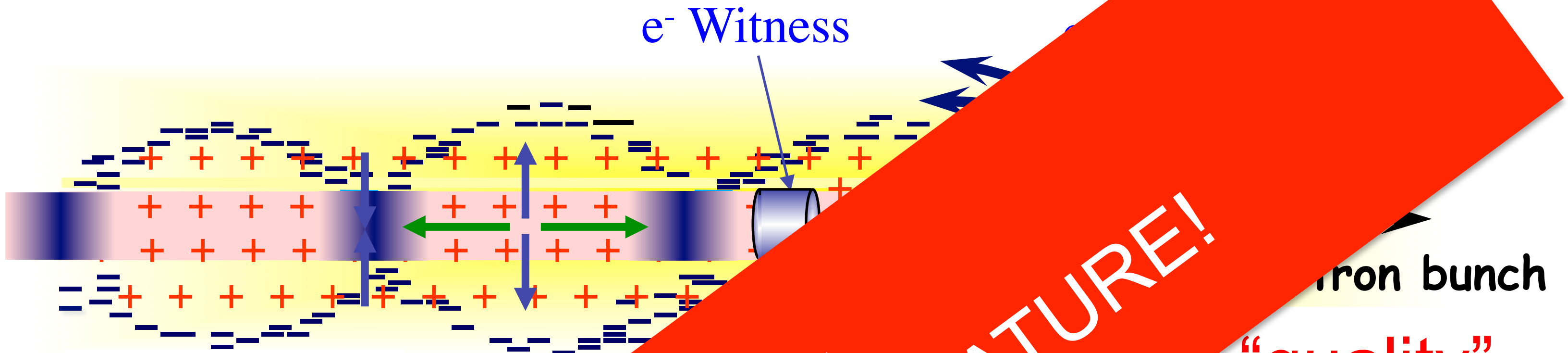
SLAC FACET

E200

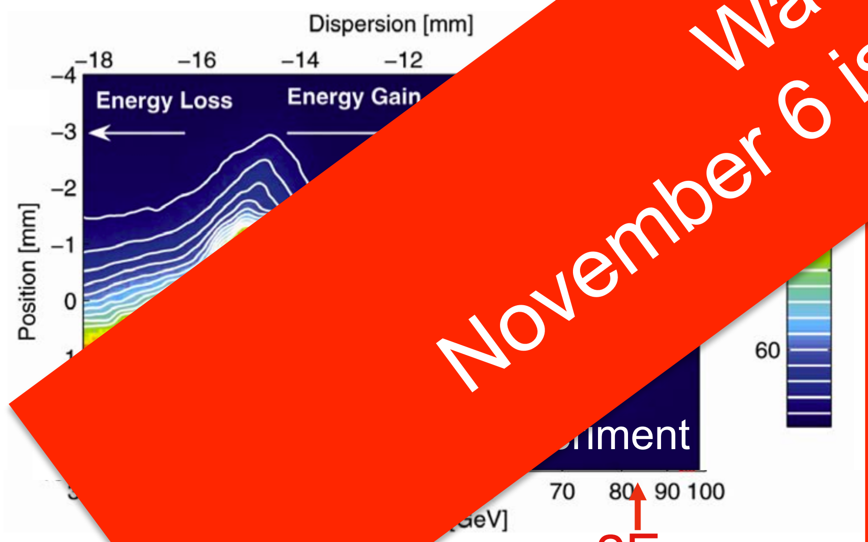
Hogan, NJP 12, 055030 (2010)



PLASMA WAKEFIELD ACCELERATOR (e



"quantity"



42 => eV in 85cm! 50GeV/m

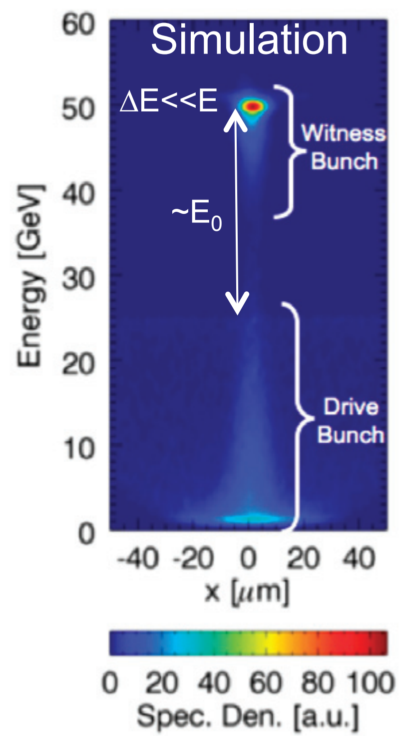
Watch for:
November 6 issue of NATURE!

CET

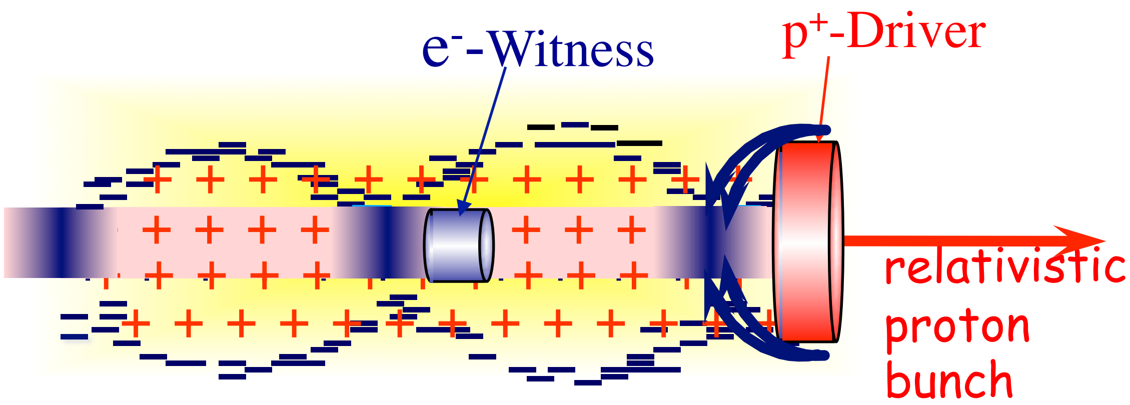
E200

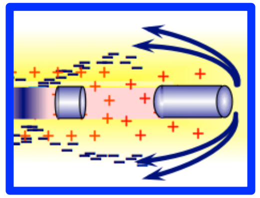
Hogan,
NJP 12,
055030 (2010)

"quality"



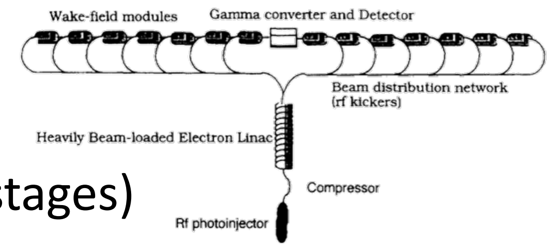
p+-DRIVEN PWFA? YES BUT WHY?

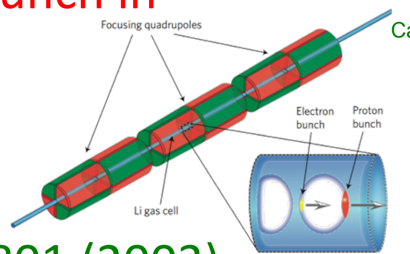




- ✧ILC, 0.5TeV bunch with $2x10^{10}e^-$ ~1.6kJ
- ✧SLAC, 20GeV bunch with $2x10^{10}e^-$ ~60J
- ✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)
- ✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- ✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- ✧Large average gradient! (≥1GeV/m, 100's m)
- ✧Wakefields driven by e⁺ bunch: Blue, PRL 90, 214801 (2003)

J. Rosenzweig et al. / Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543

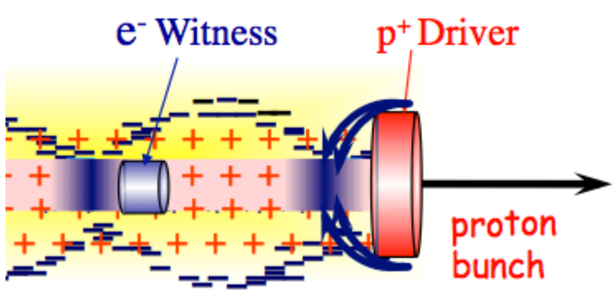




Caldwell, Nat. Phys. 5, 363, (2009)

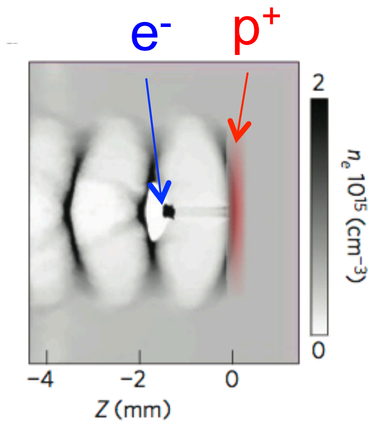
PROTON-DRIVEN PWFA

Caldwell, Nat. Phys. 5, 363, (2009)

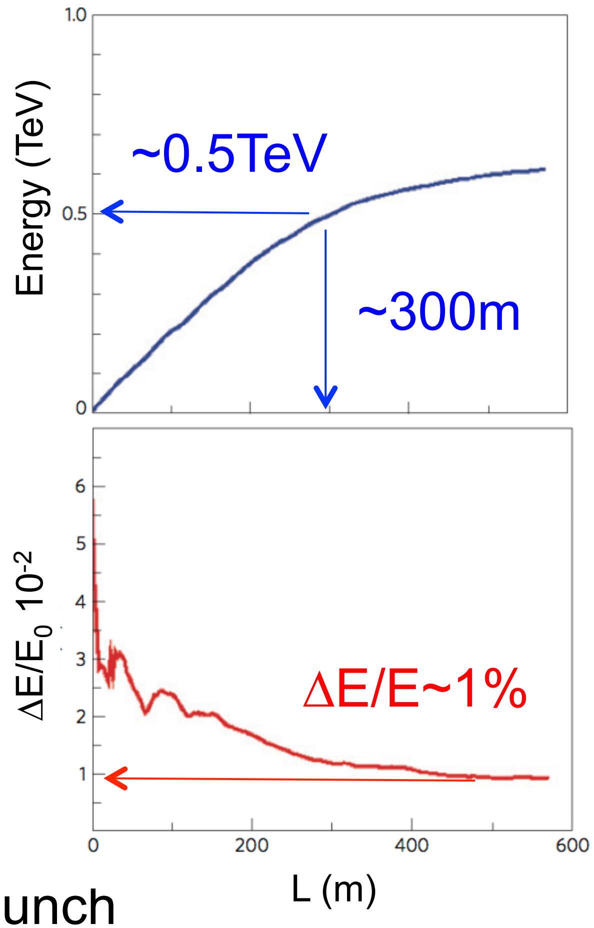


e^-:	p^+:
E_0=10GeV	E_0=1TeV
	σ_z=100µm
N=10^{10}	N=10^{11}
W_0=16J	W_0=16kJ
W_f=1kJ	

Single Stage



Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_P/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$T\,m^{-1}$
Magnet length		0.7	m



- Accelerate an e^- bunch on the wakefields of a p^+ bunch
- Single stage, no gradient dilution
- Gradient ~1 GV/m over 100's m
- Operate at lower n_e ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

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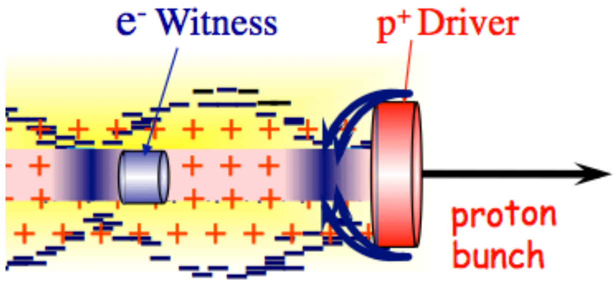
PROTON-DRIVEN PWFA

Caldwell, Nat. Phys. 5, 363, (2009)

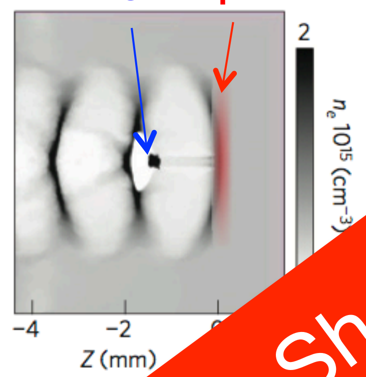
AWAKE

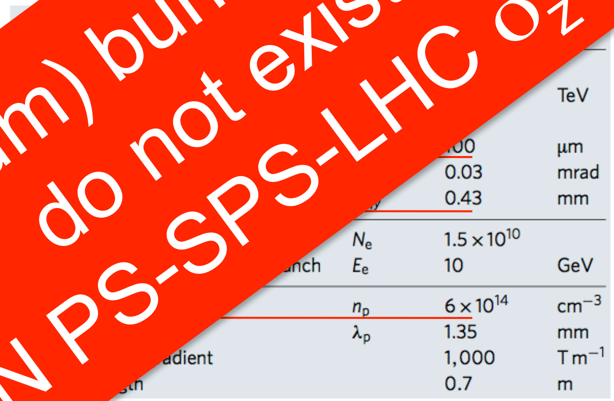


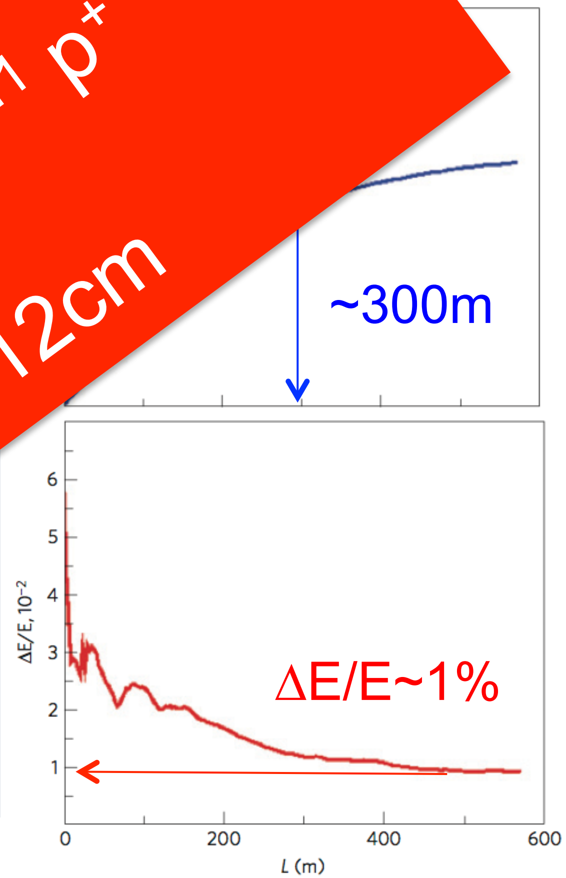
e^-: E_0=10GeV N=10^{10} W_0=…

p^+: E_0=1T…

Single Stage







Short (100µm) bunches with 10^{11} p^+
do not exist!!!
CERN PS-SPS-LHC σ_z~12cm

- ✧ …n the wakefields of a p^+ bunch
- ✧ …ient dilution
- ✧ Gr… m over 100's m
- ✧ Oper… ower n_e, larger $(\lambda_{pe})^3$, easier life …

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SELF-MODULATION INSTABILITY (SMI)

✧CERN p^+ bunches (PS, SPS, LHC) ~12cm long

✧$E_{WB} \sim \omega_{pe} \sim n_e^{1/2}$ and $\sigma_z \sim n_e^{-1/2}$

PRL 104, 255003 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Self-Modulation Instability of a Long Proton Bunch in Plasmas

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Institut für Theoretische Physik I, Heinrich-Heine-Universität, Düsseldorf D-40225 Germany

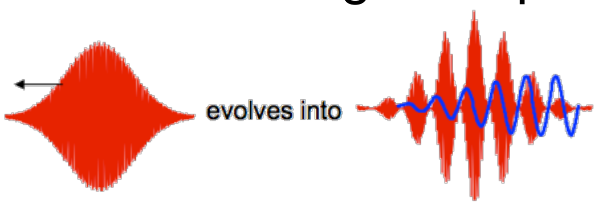
Konstantin Lotov
Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia
(Received 16 April 2010; published 25 June 2010)

An analytical model for the self-modulation instability of a long relativistic proton bunch propagating in uniform plasmas is developed. The self-modulated proton bunch resonantly excites a large amplitude plasma wave (wakefield), which can be used for acceleration of plasma electrons. Analytical expressions for the linear growth rates and the number of exponentiations are given. We use full three-dimensional particle-in-cell (PIC) simulations to study the beam self-modulation and transition to the nonlinear stage. It is shown that the self-modulation of the proton bunch competes with the hosing instability which tends to destroy the plasma wave. A method is proposed and studied through PIC simulations to circumvent this problem, which relies on the seeding of the self-modulation instability in the bunch.

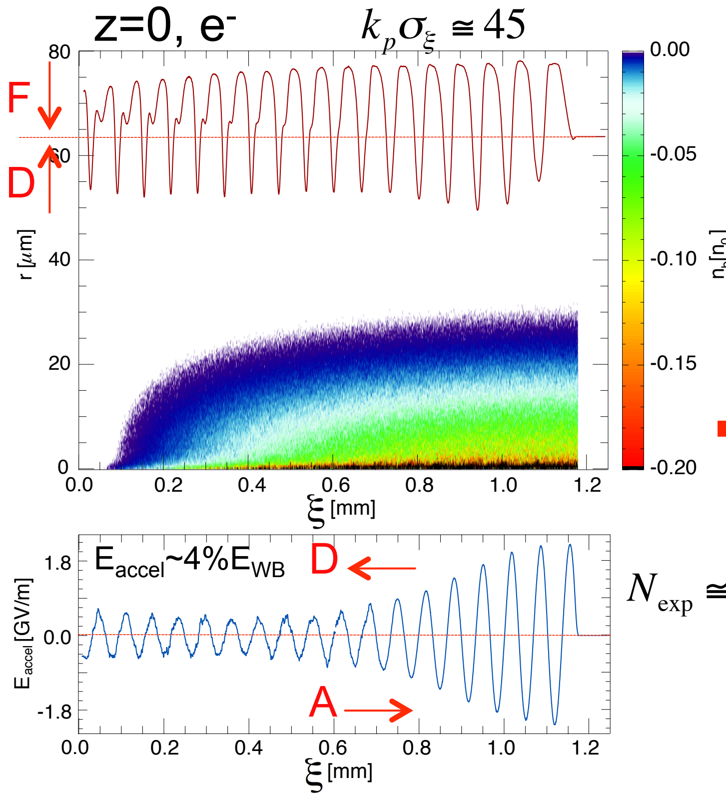
DOI: 10.1103/PhysRevLett.104.255003 PACS numbers: 52.35.−g, 52.40.Mj, 52.65.−y

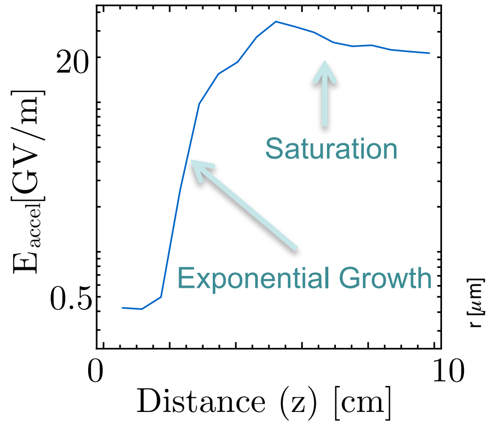
✧Idea developed "thanks" to the non-availability of short p^+ bunches

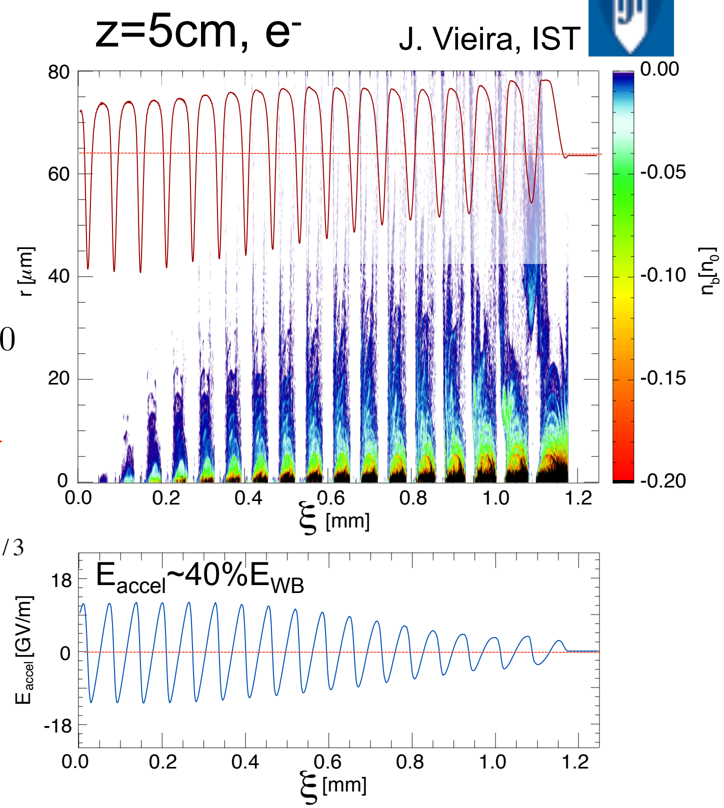
✧Very similar to Raman self-modulation of long laser pulses (LWFA of the 20th century)



Self-Modulation Instability (SMI)







$$N_{\exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$

Grows along the bunch & along the plasma

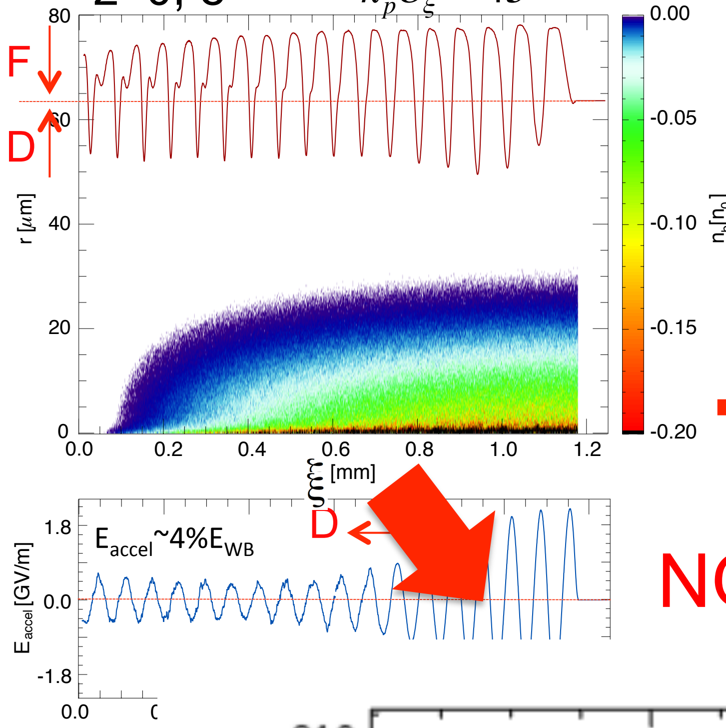
Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

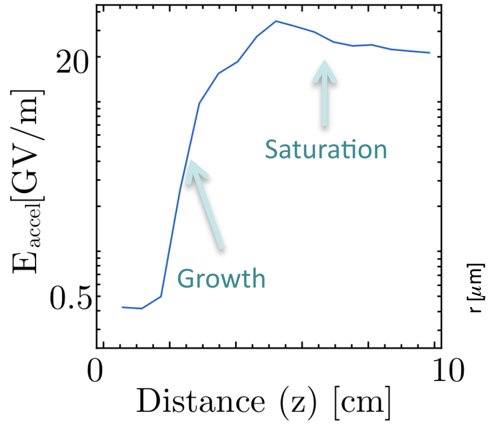
- ✧Initial small transverse wakefields modulate the bunch density
- ✧Associated longitudinal wakefields reach large amplitude through resonant excitation

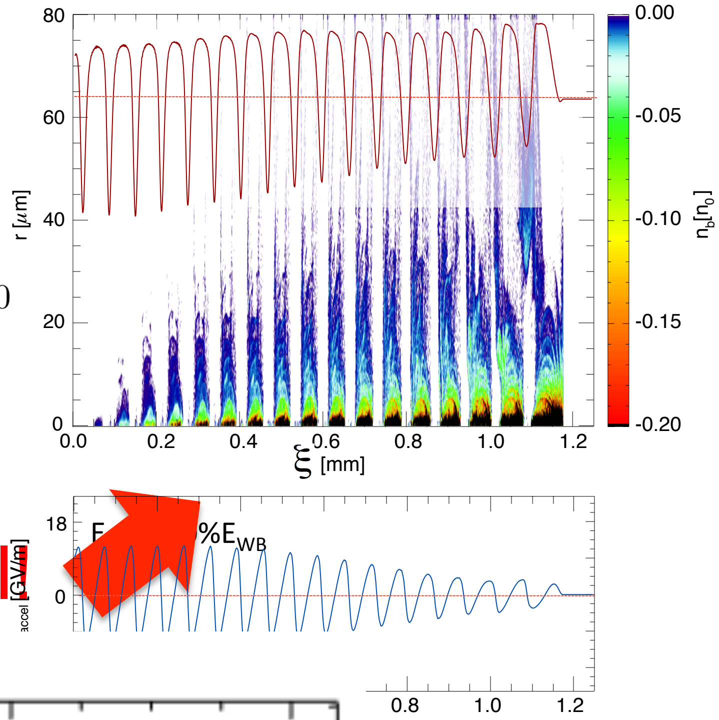
J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

SELF-MODULATION INSTABILITY (SMI)

Vieira et al., Phys. Plasmas 19, 063105 (2012).

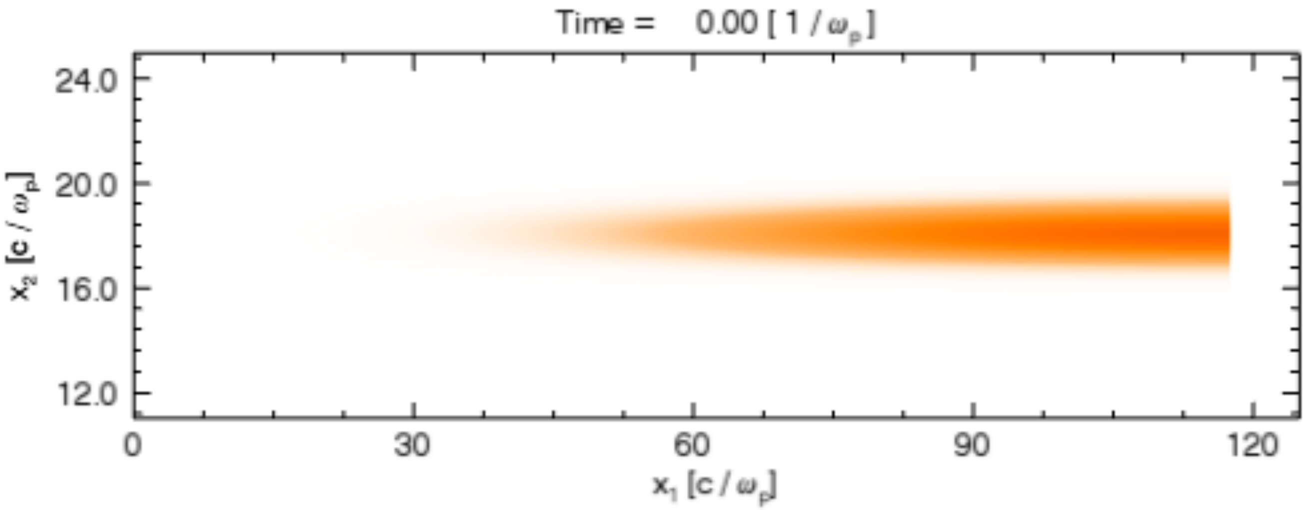






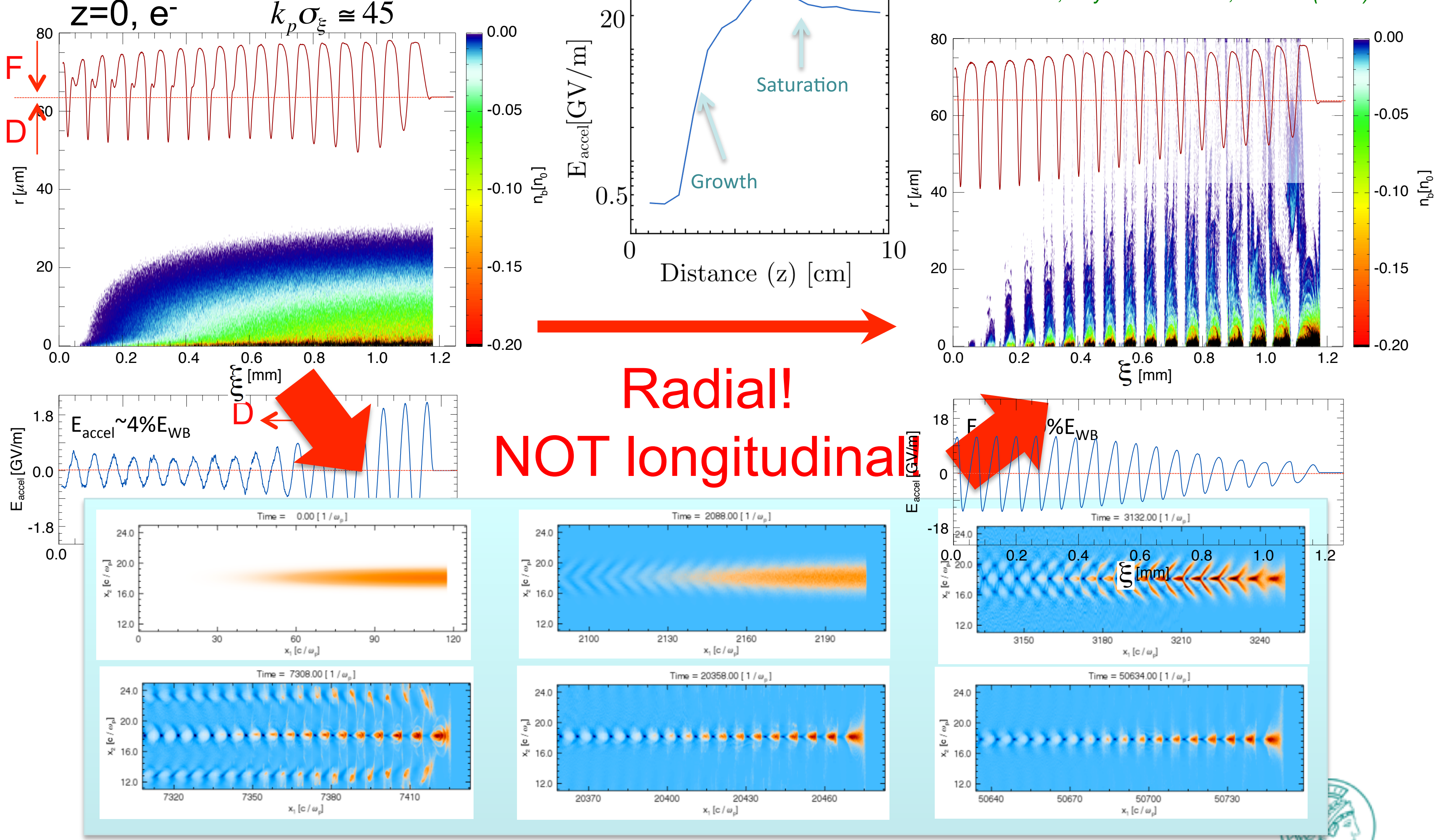
Radial!

NOT longitudinal!



SELF-MODULATION INSTABILITY (SMI)

Vieira et al., Phys. Plasmas 19, 063105 (2012).



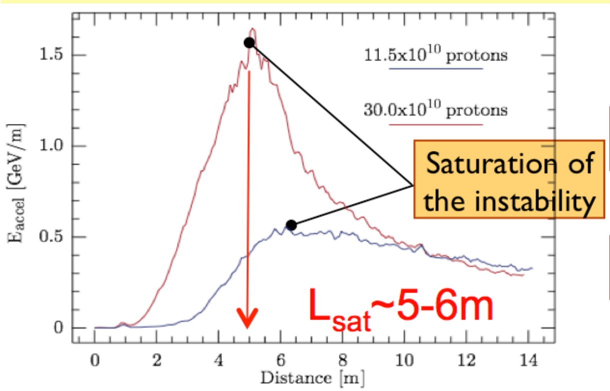
SM-PWFA PARAMETERS

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

✧Experimental parameters determined by beam parameters

✧CERN AWAKE

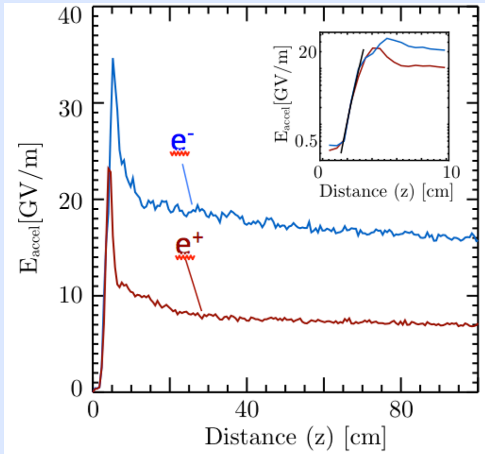
- p^+-driven
- SMI saturates in ~5m
- Study SMI or p^+-bunches
- Remain in ~linear PWFA regime
- ~GV/m over 10^+ m
- Externally inject e^-
- Accelerator experiments



Parameter	PDPWFA	PWFA
$n_e[\mathrm{cm}^{-3}]$	6×10^{14}	2.3×10^{17}
$f_{pe}[\mathrm{GHz}]$	220	4′300
$\sigma_r[\mu m]$	200	10
$\sigma_r[c/\omega_{pe}]$	0.9	0.9
$\sigma_\xi[\mathrm{cm}]$	12	5×10^{-2}
$\sigma_\xi[c/\omega_{pe}]$	553	45
σ_ξ/λ_{pe}	88	7
$E_0[\mathrm{GeV}]$	400	20.5
γ_0	426	40′000
N_{part}	30×10^{10}	2×10^{10}
n_b/n_0	2×10^{-2}	10^{-1}
$L^{plasma}[\mathrm{m}]$	10	1
$L^{plasma}[c/\omega_{pe}]$	46′056	90′173
L^{plasma}/λ_{pe}	7′330	14′352
$\epsilon_N[\mathrm{mm\cdot mrad}]$	3.83	50

✧SLAC E209

- e^-/e^+-driven
- SMI saturates in ~5cm
- Compare SMI of e^-/e^+ bunches
- Reaches nonlinear PWFA regime
- >10GV/m
- Multi GeV energy gain (drive particles) in ~1m
- SMI physics

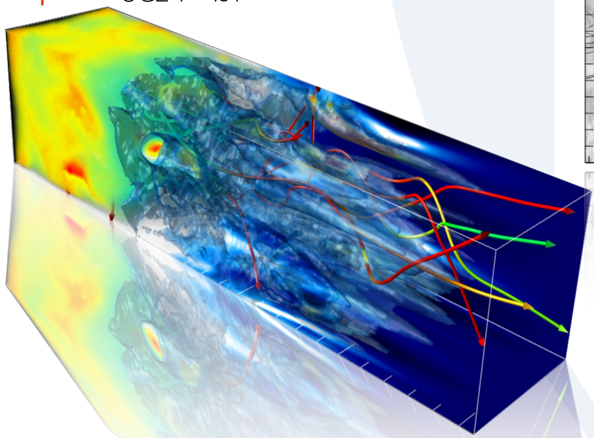


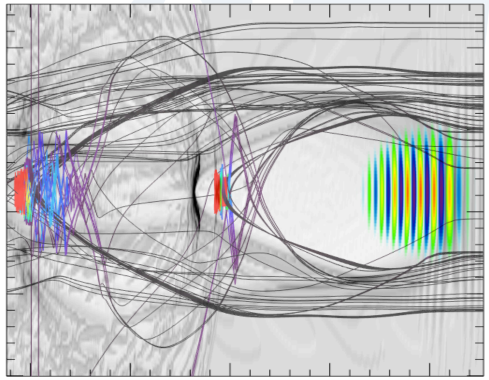
SMI-PWFA SIMULATIONS

OSIRIS 2.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

Patric Muggli | May 23rd 2012 | IPAC - New Orleans Louisiana, USA

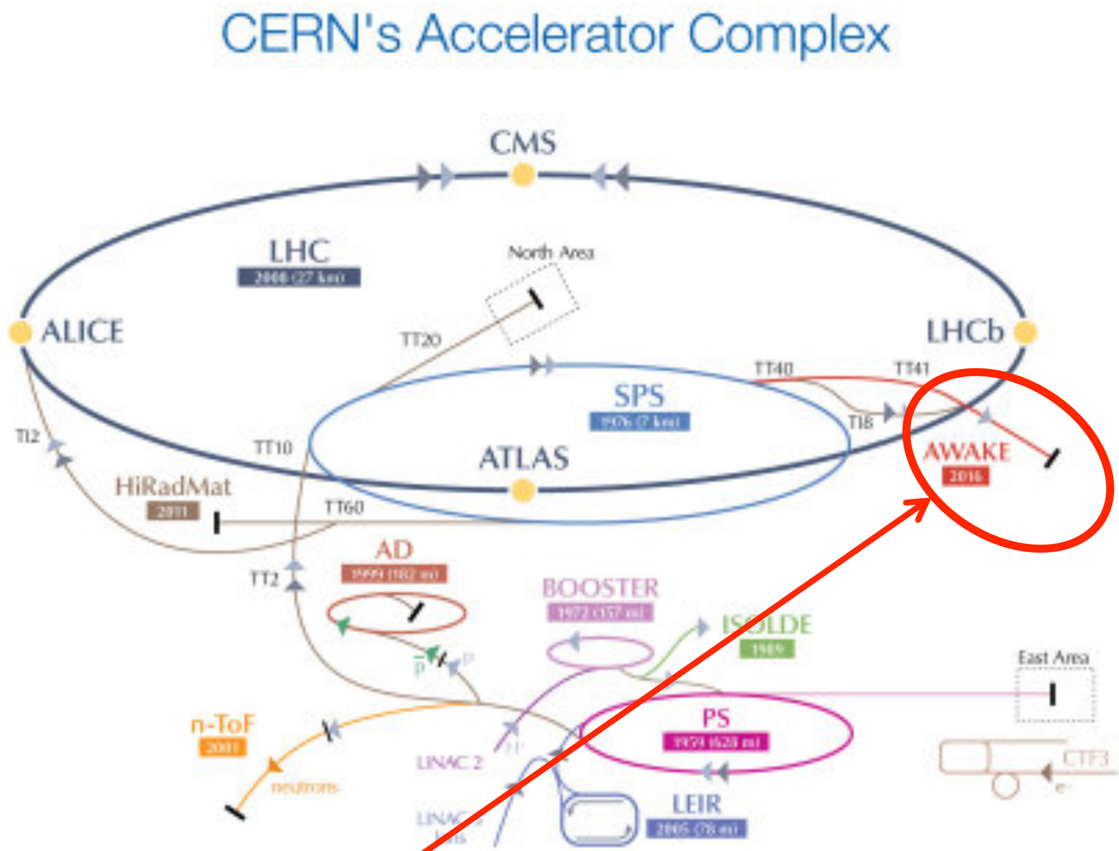
Benchmarking with (for AWAKE only!):

- ✧OSIRIS: R. A. Fonseca et al., Lect. Notes Comput. Sci. 2331, 342 (2002)
- ✧VLPL A: Pukhov, J. Plasma Phys. 61, 425 (1999)
- ✧LCODE: K. V. Lotov, Phys. Rev. ST Accel. Beams 6, 061301 (2003)

OUTLINE

- Introduction to Plasma Wakefield Accelerator (PWFA)
- Introduction to the self-modulation instability (SMI)
- SMI PWFA experiments at CERN with p^+: AWAKE
- SMI experiments at SLAC E209 with e^-/e^+
- Linear PWFA – SMI seeding at BNL-ATF
- Summary

PROTON BEAMS @ CERN



Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	400	400
N_p (10^{10})	13	10.5	30
$\Delta E/E_0$ (%)	0.05	0.03	0.03
σ_z (cm)	20	12	12
ε_N (mm-mrad)	2.4	3.6	3.6
σ_r^* (µm)	400	200	200
β^* (m)	1.6	5	5

$n_e \sim 7\text{x}10^{14}\text{cm}^{-3}$ for $k_p\sigma_r \approx 1$
$\lambda_{pe} \sim 1.3\text{mm} << \sigma_z$
$f_{pe} \sim 240\text{GHz}$
$L_p \sim 10\text{m} \sim 2\beta^*$

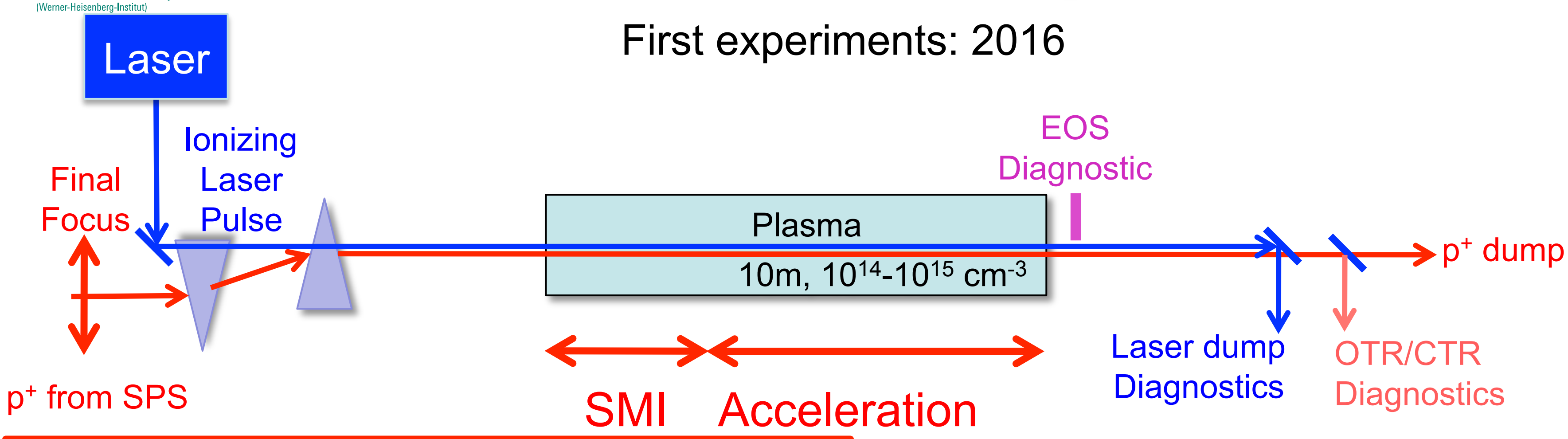
AWAKE experimental area

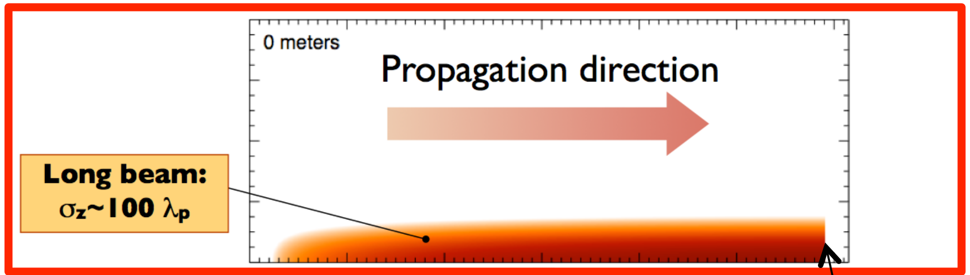
✧SPS beam: high energy, small σ_r^*, long β^*

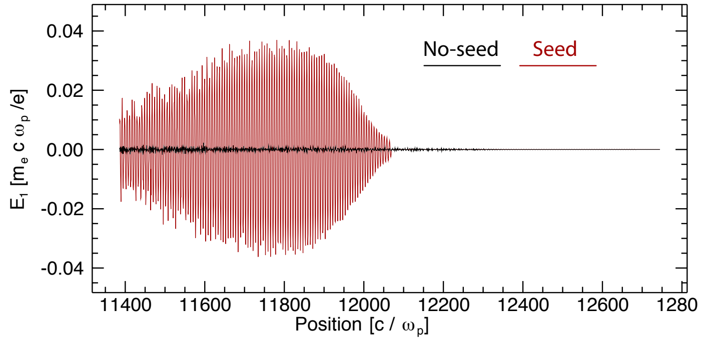
✧Initial goal: ~GeV gain by externally injected e^-, in 5-10m of plasma in self-modulated p^+ driven PWFA

AWAKE EXPERIMENT @ CERN

First experiments: 2016







✧No seed no SMI (over 10m)

"Sharp" ($<<\lambda_{pe}$) start of the beam/plasma interaction for SMI seeding
AWAKE: will seed with ionization front!

*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

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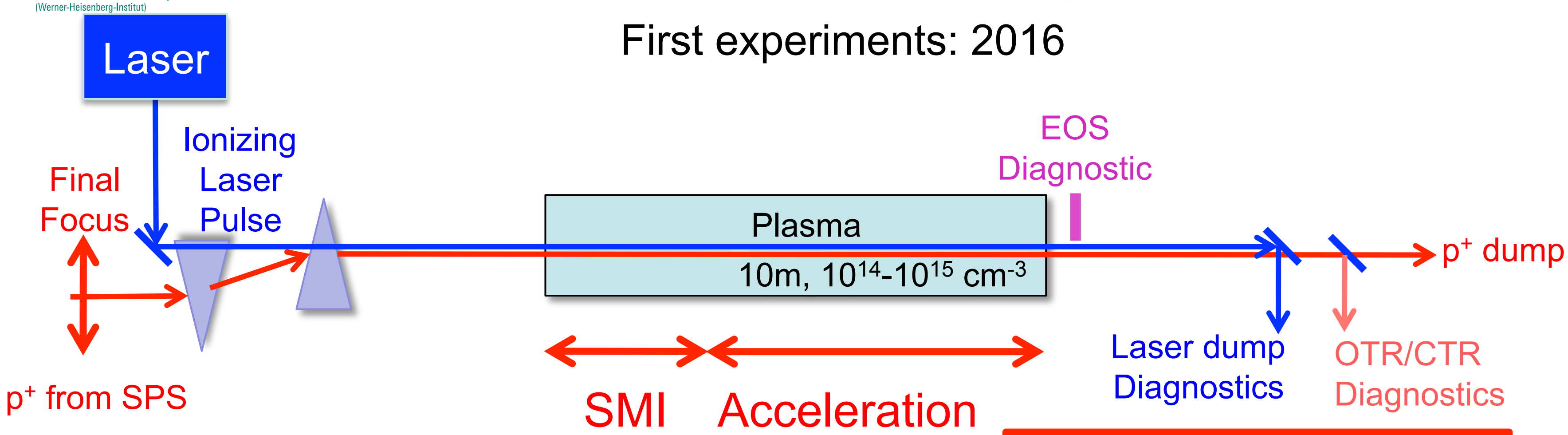
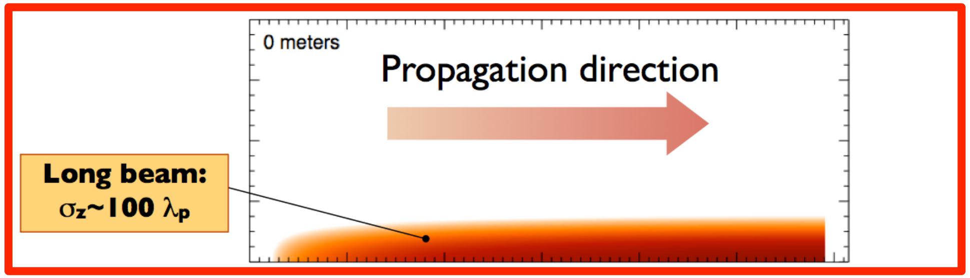
(Werner-Heisenberg-Institut)

AWAKE EXPERIMENT @ CERN

First experiments: 2016





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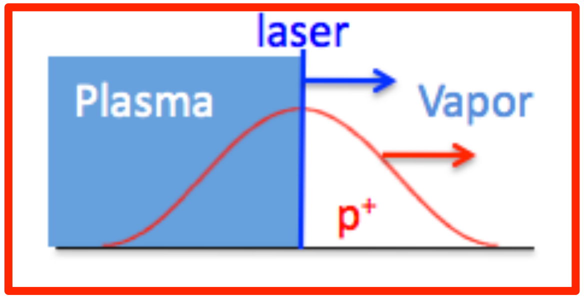
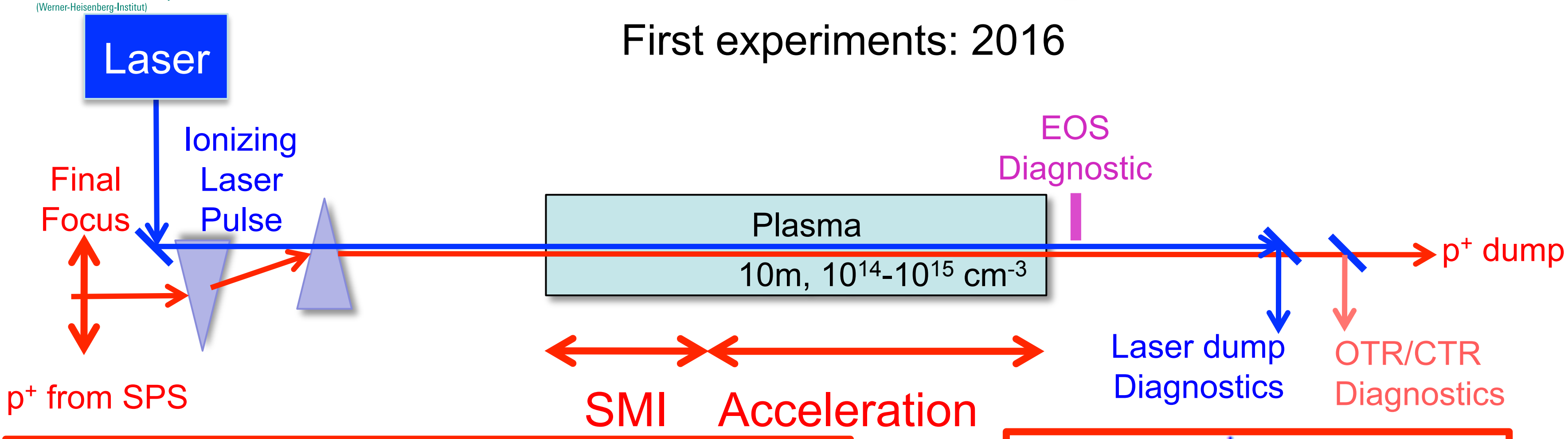


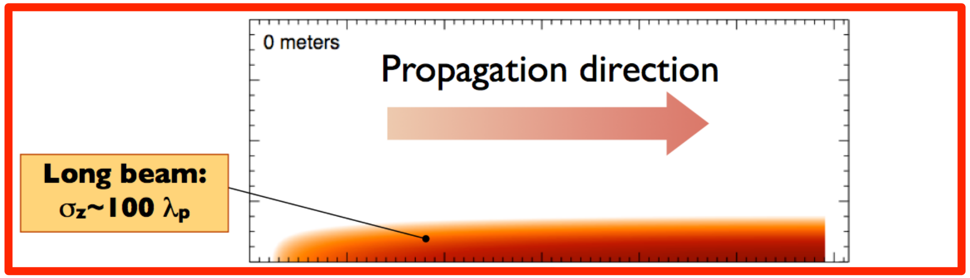
- ✧Short laser pulse creates the plasma and seeds the SMI
- ✧σ_z~12cm >> λ_{pe}~1.2mm (n_e~10^{14}cm^{-3}) => Self-modulation Instability (SMI)*

*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

AWAKE EXPERIMENT @ CERN

First experiments: 2016





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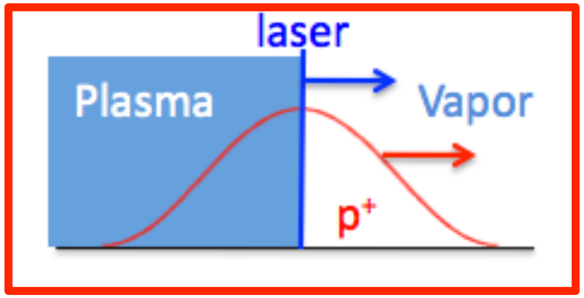

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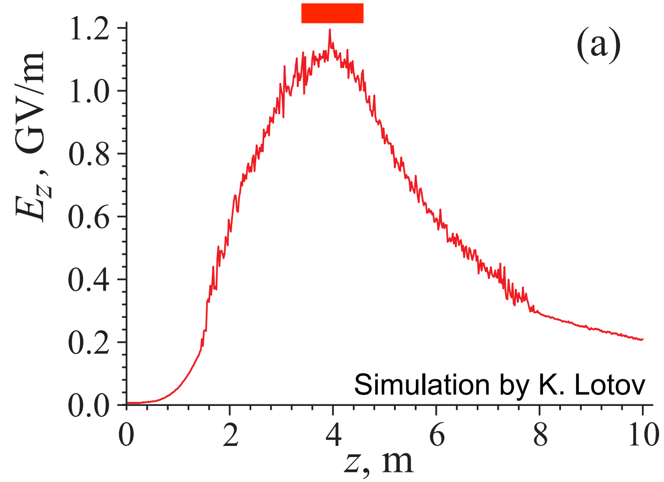
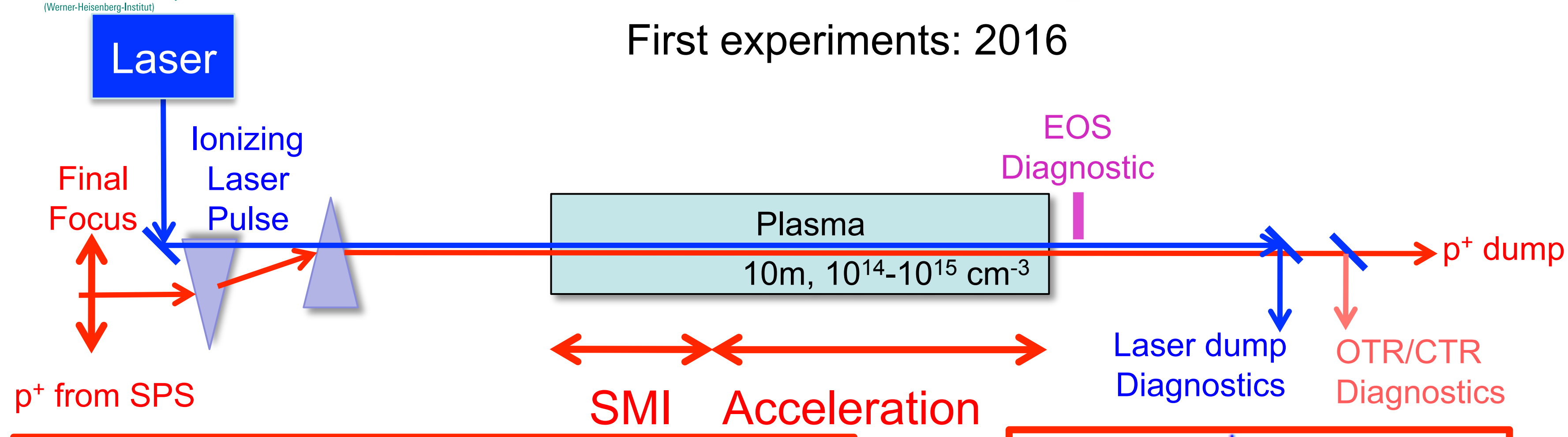
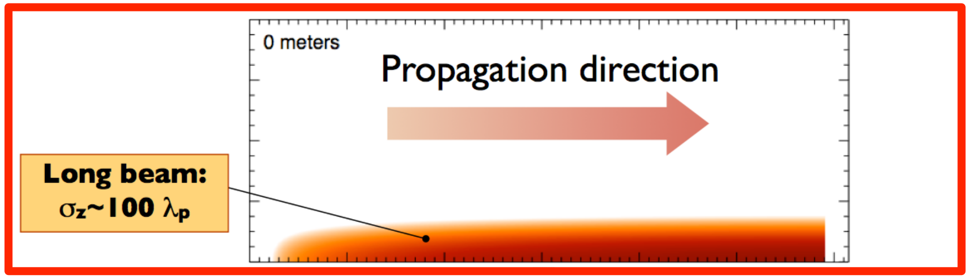


✧ The wakefields grow …

AWAKE EXPERIMENT @ CERN

First experiments: 2016





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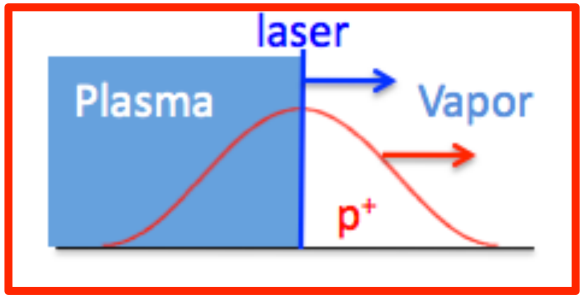

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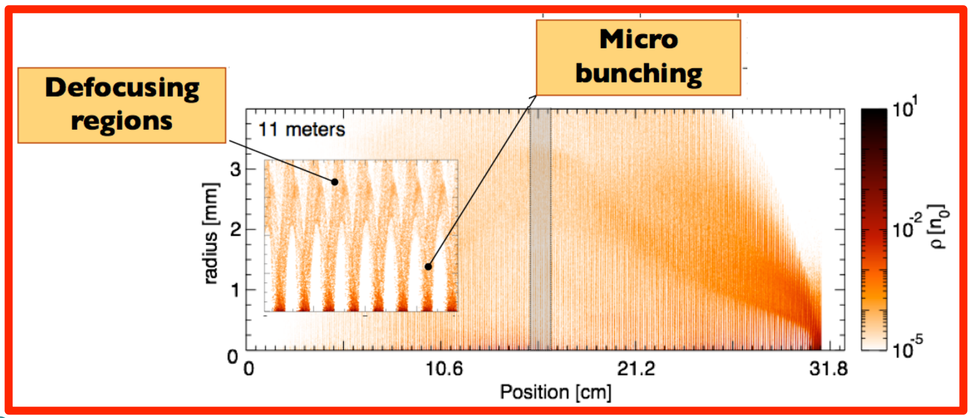
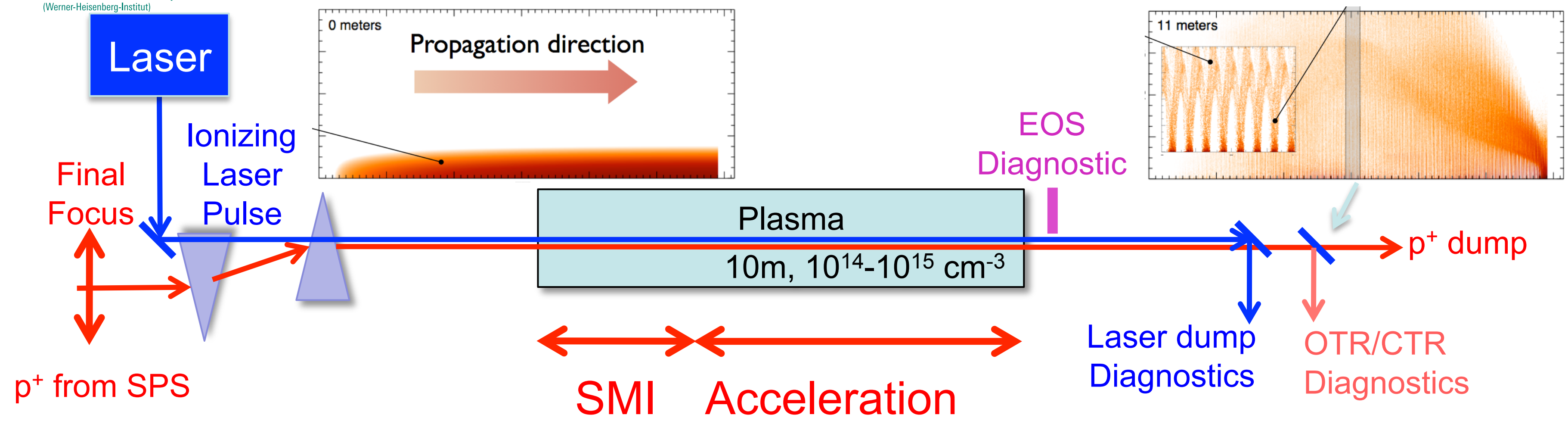
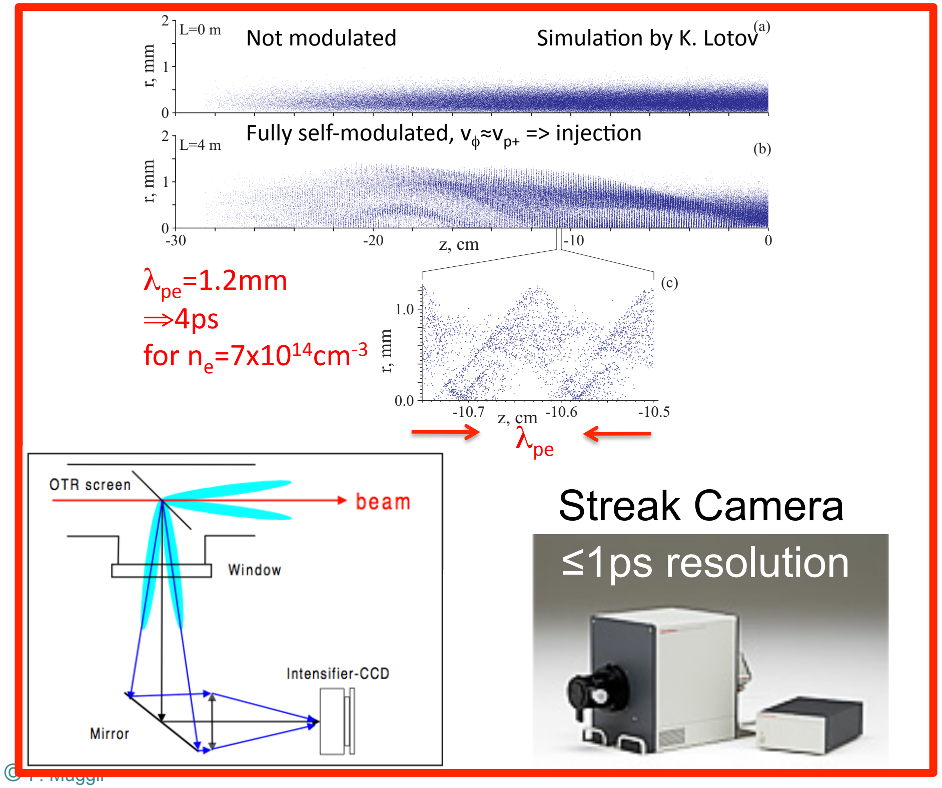
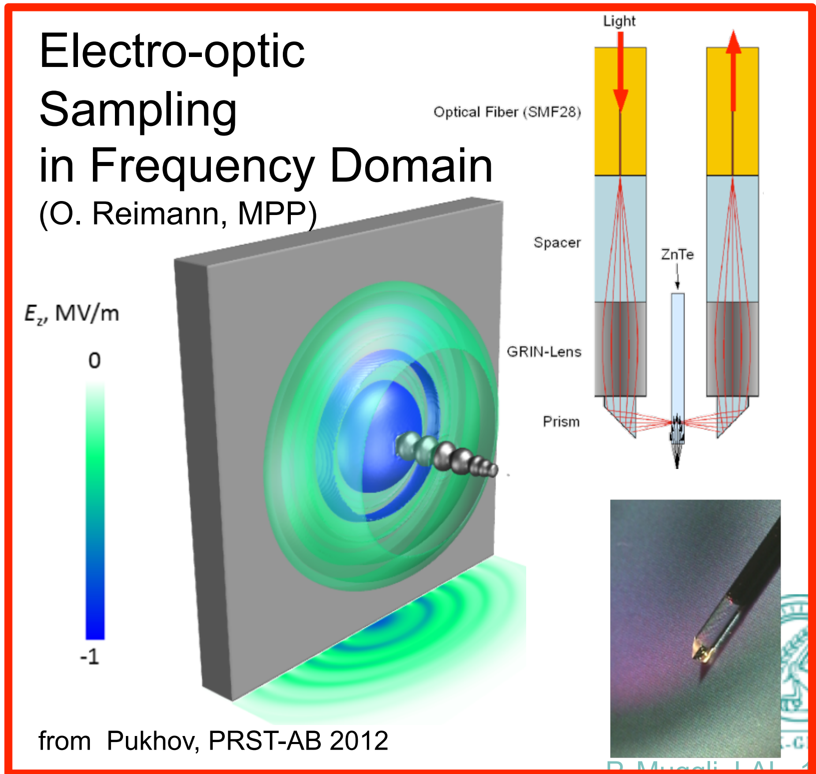


- The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~10^{14}cm^{-3})

SMI DIAGNOSTICS







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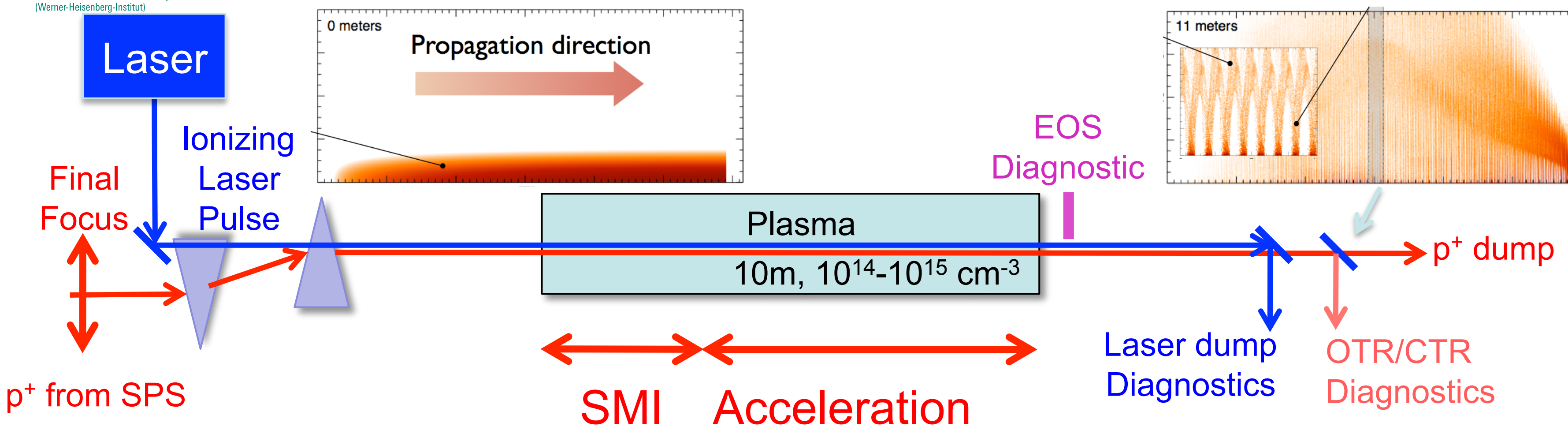
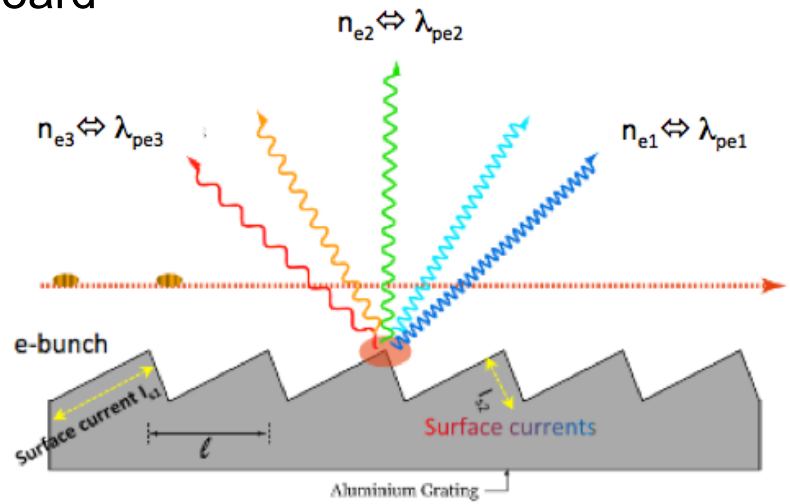
SMI DIAGNOSTICS



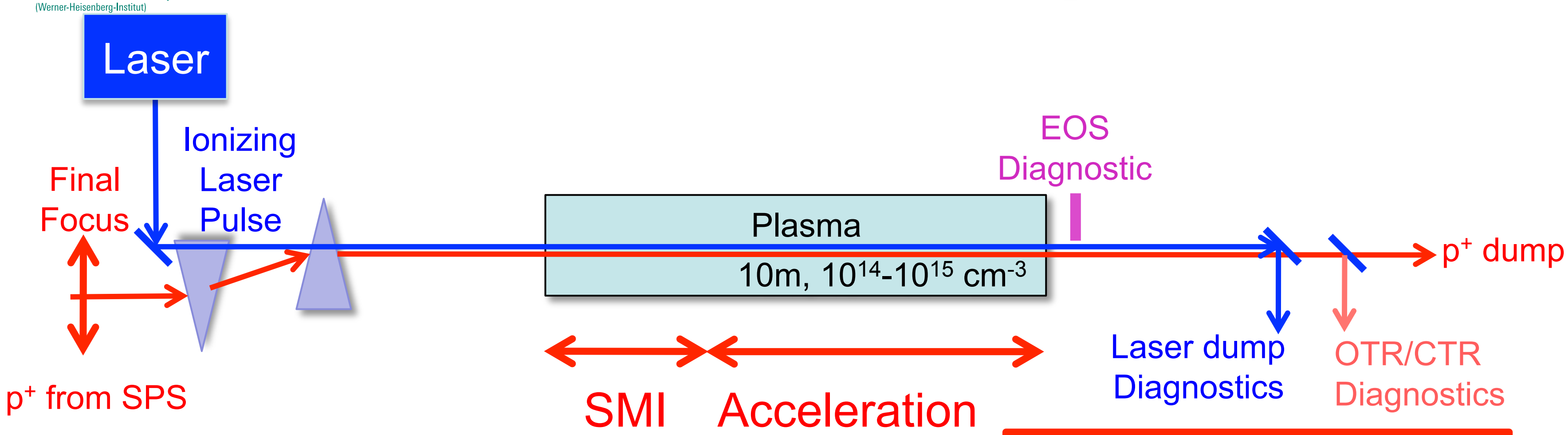
✧ Possibility: Smith-Purcell radiation, investigated by AWAKE Physics and Experiment Board

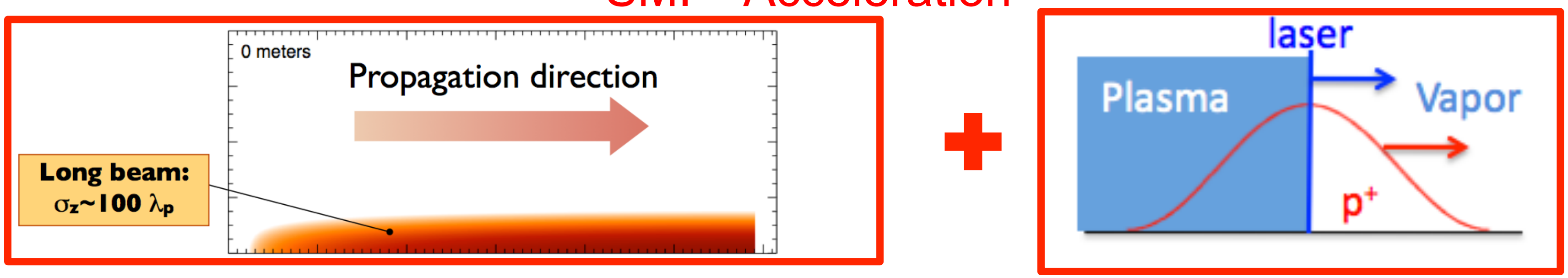


✧ Modulation wavelength for each event

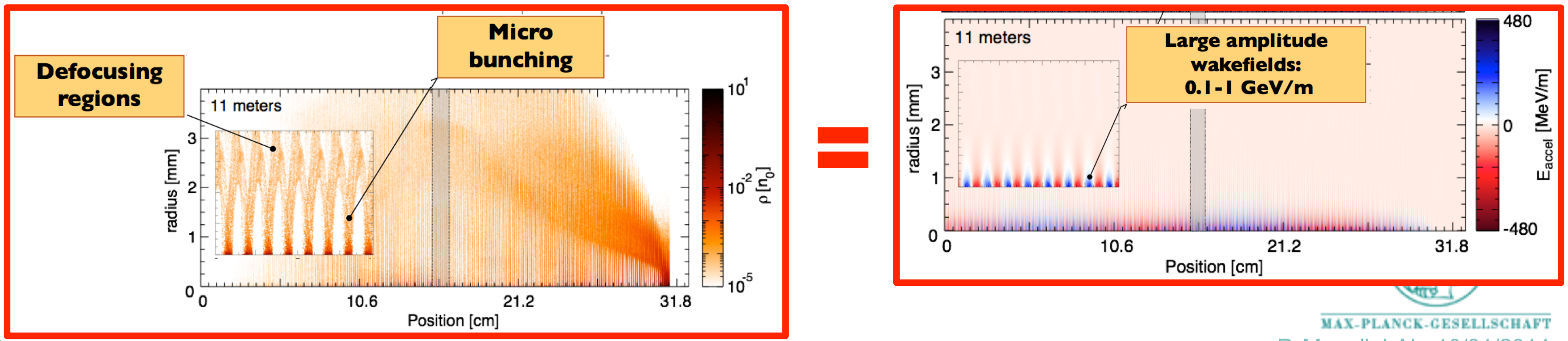
✧ Sensitive to radial modulation?

AWAKE EXPERIMENT @ CERN

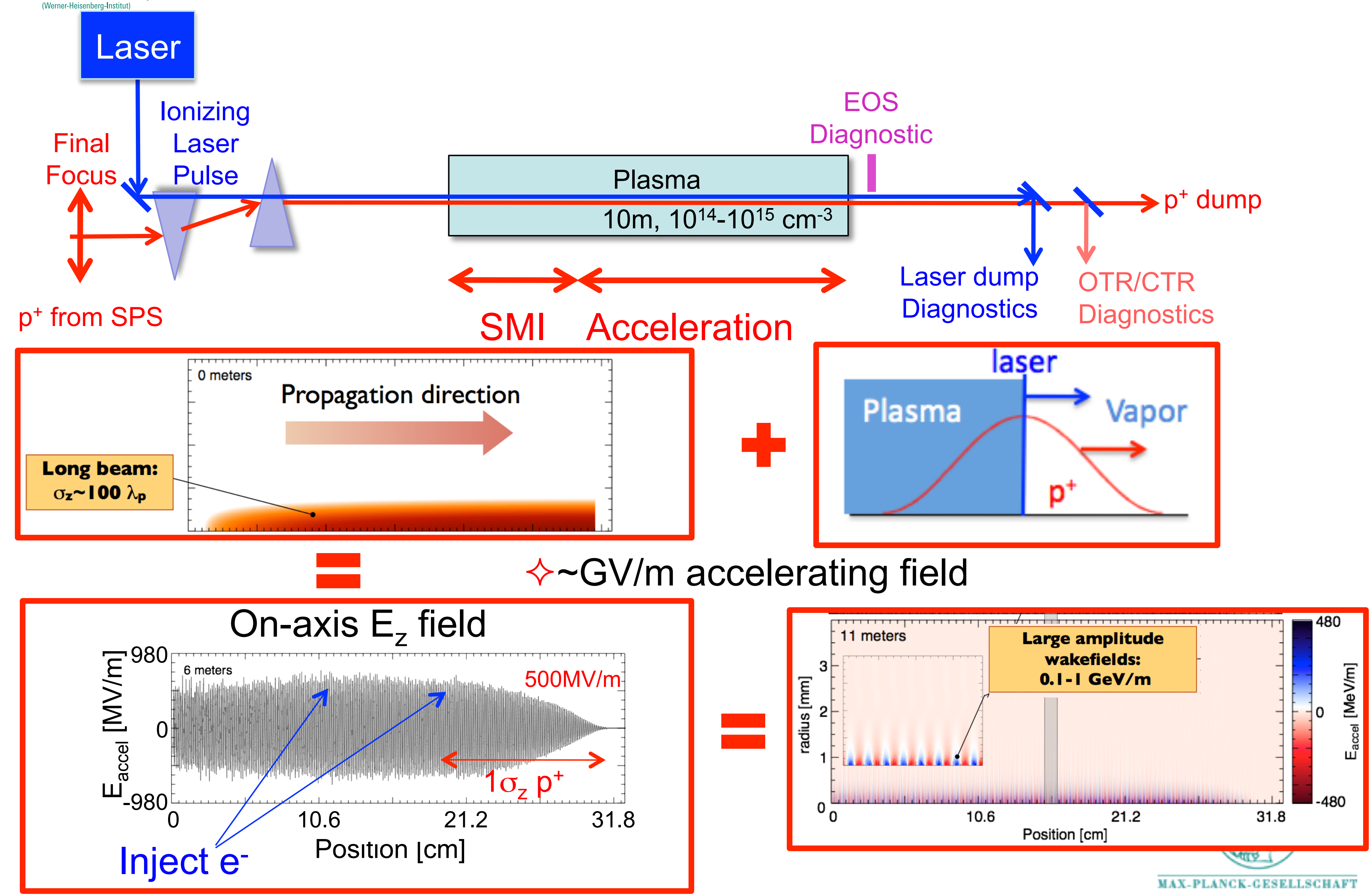




✧The SM p^+ bunch resonantly drives wakefields



AWAKE EXPERIMENT @ CERN

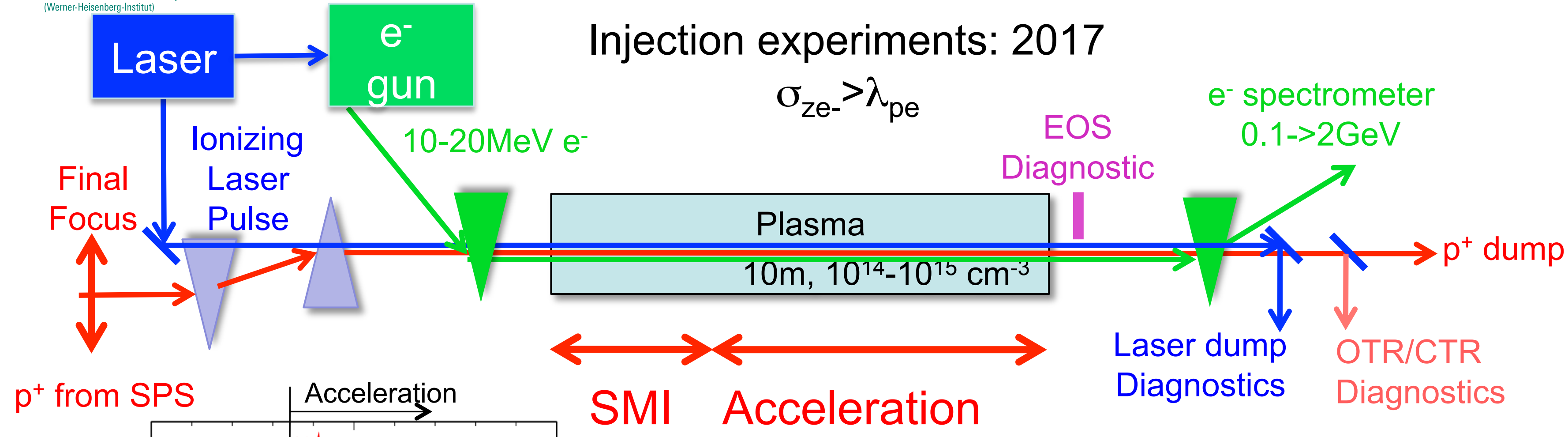


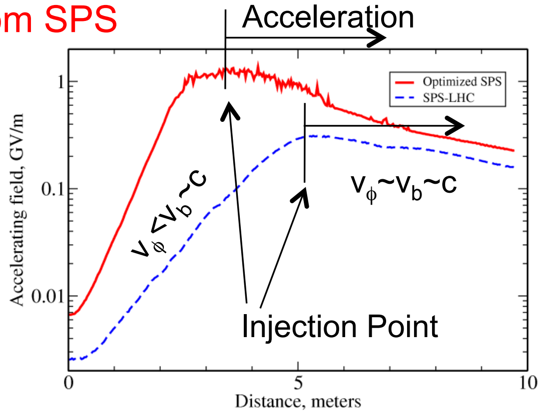
© P. Muggli

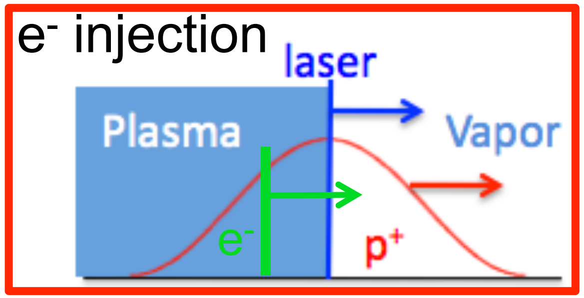
WAKEFIELDS SAMPLING / ACCELERATION

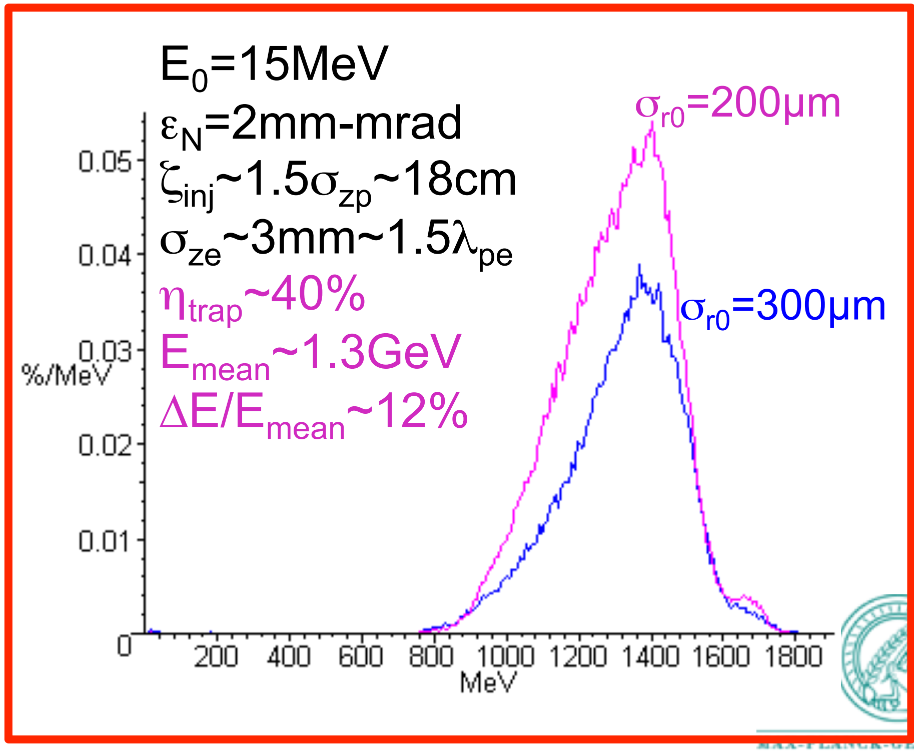
Injection experiments: 2017

$\sigma_{ze-} > \lambda_{pe}$









✧ Accelerate e- to multi-GeV energies with ~GeV/m gradient

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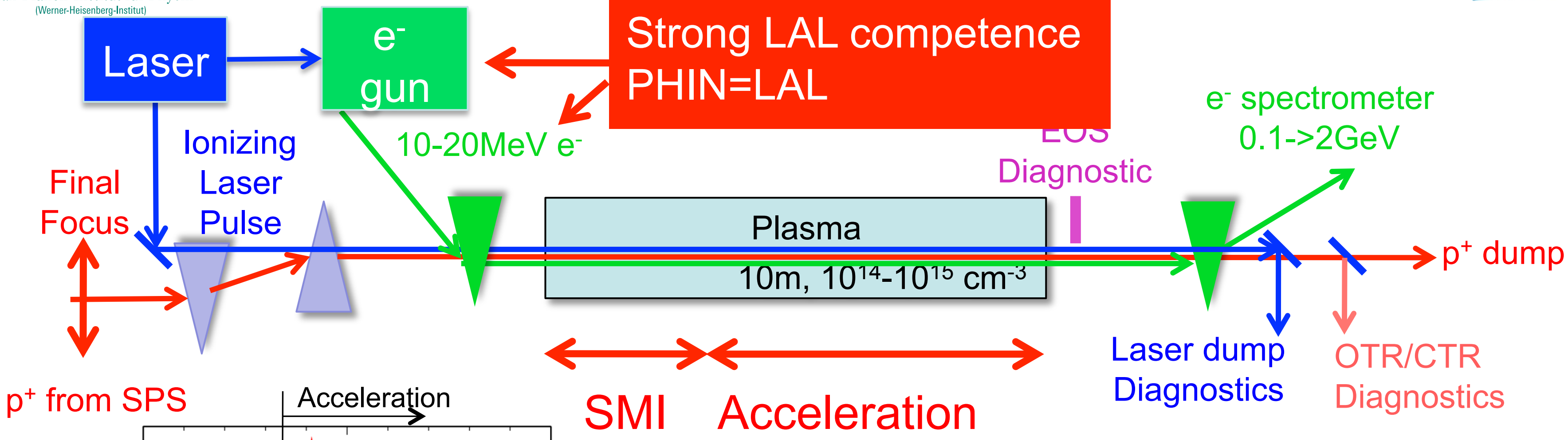
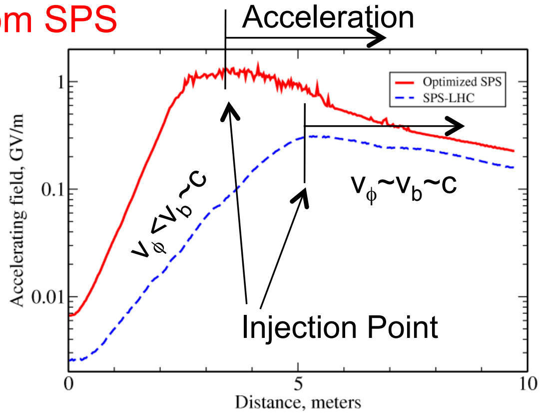
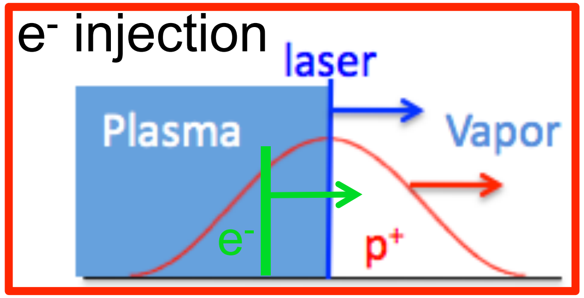
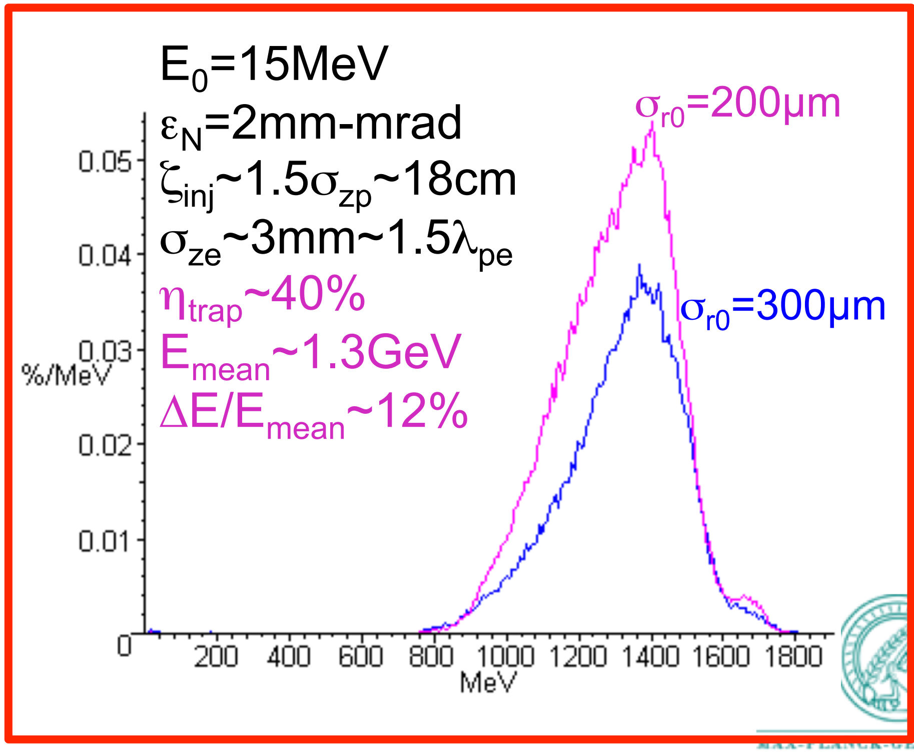
WAKEFIELDS SAMPLING / ACCELERATION









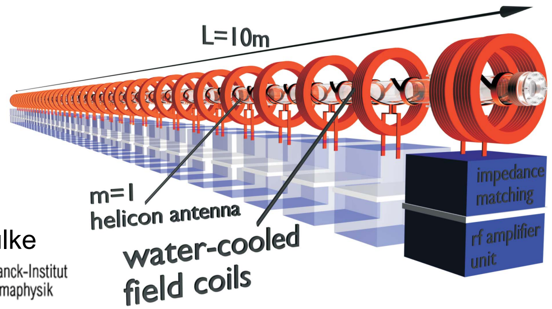
✧ Accelerate e^- to multi-GeV energies with ~GeV/m gradient

GOALS OF AWAKE EXPERIMENT

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

- ✧study the physics of p^+ bunch SMI (radial modulation, seeding, …)
- ✧probe the longitudinal (accelerating) wakefields with externally injected e^-
- ✧study injection dynamics (side or on-axis injection) of e^-
- ✧produce multi-GeV e^- with ~GV/m gradient maintained over m-distances
- ✧develop long, scalable and uniform plasma cells
- ✧develop schemes for the production of short p^+ bunches

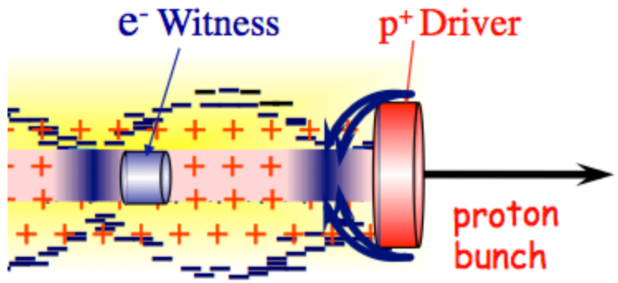
✧Experiment approved Fall 2013
SMI experiments 2016
e^- injection 2017



O. Grülke
IPP Max-Planck-Institut für Plasmaphysik

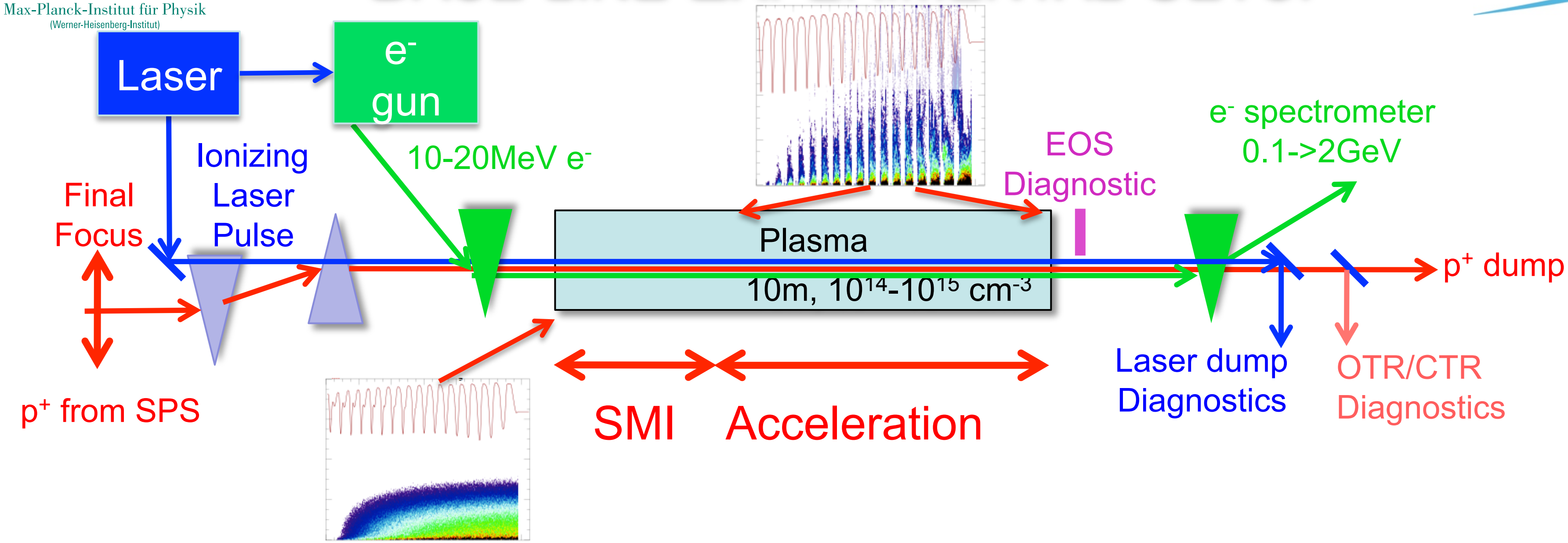
✧Set-up a comprehensive and long term p^+-driven plasma-based accelerator program at CERN

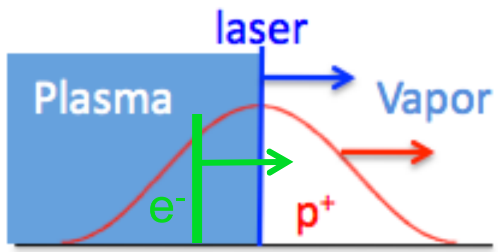
✧Explore applications for a p^+-driven PWFA



MAX-PLANCK-GESELLSCHAFT

BASE-LINE EXPERIMENTAL SETUP





✧Laser ionization of a Rb metal vapor, 7-10m plasma, $n_e=10^{14}$-$10^{15}cm^{-3}$

✧Injection of 10-20MeV test e^- at plasma entrance ($\sigma_{ze-}>\lambda_{pe}$)

✧0.1-5GeV electron spectrometer

✧OTR + streak camera, electro-optic sampling for p^+-bunch modulation diag.

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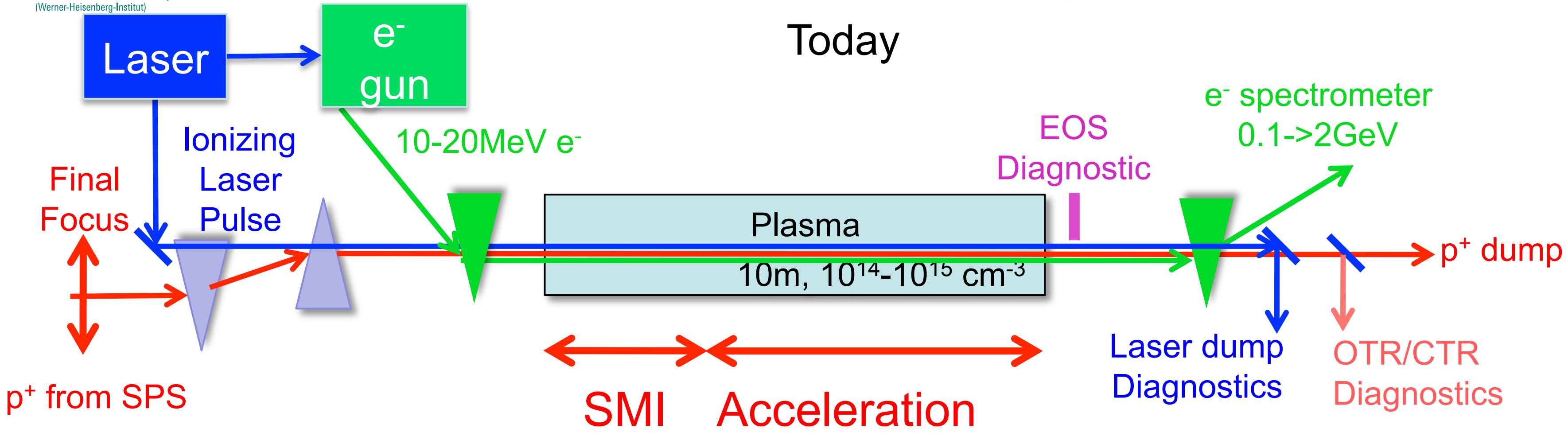
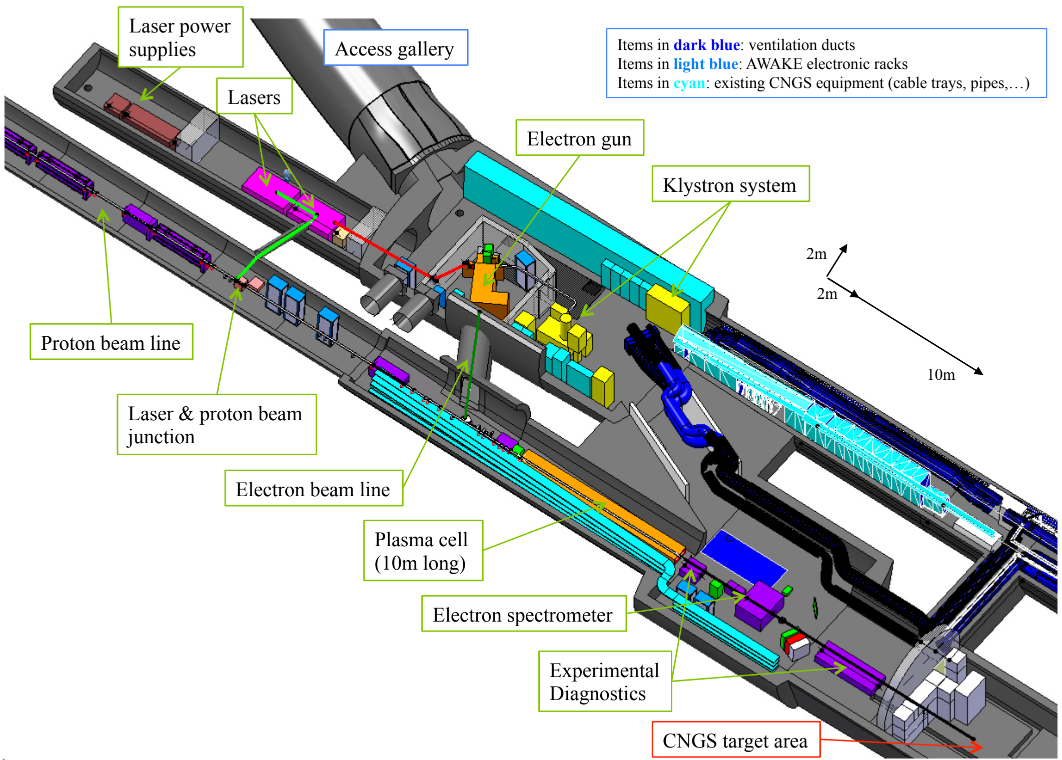
AWAKE Experiment @ CERN





- ✧ CERN team already translated our dreams into CAD drawings
- ✧ Next step: make it real!

MAX-PLANCK-GESELLSCHAFT

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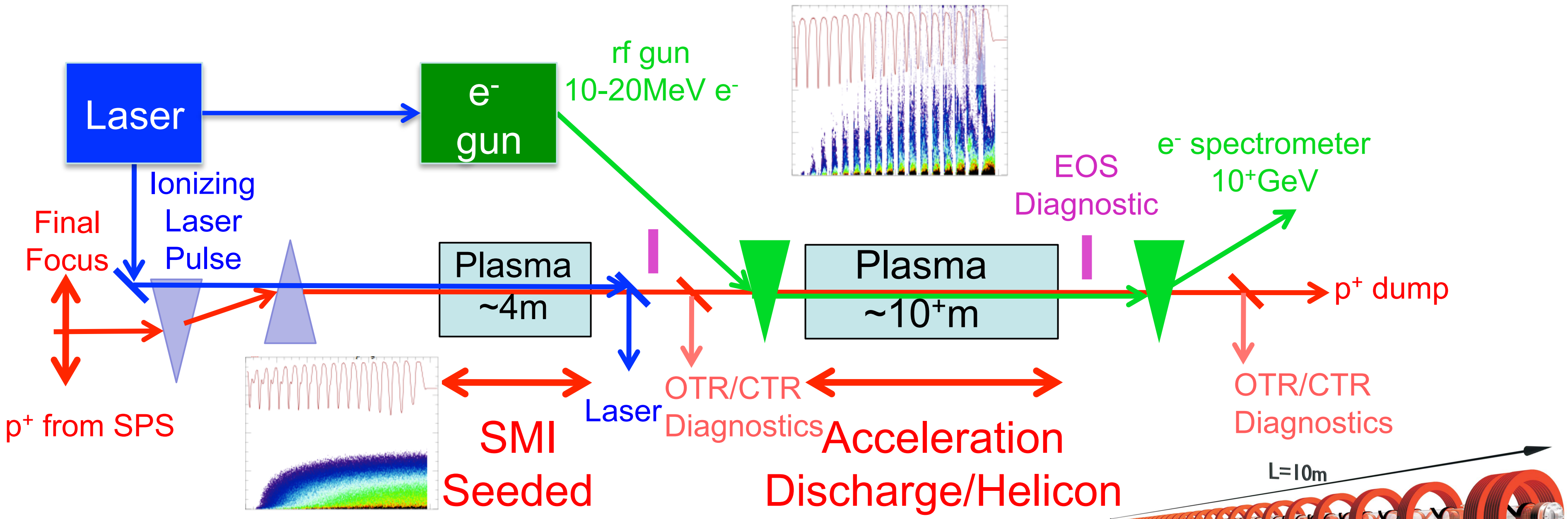
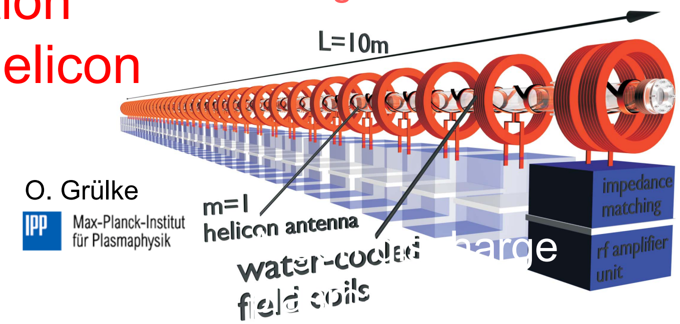
(Werner-Heisenberg-Institut)

p⁺-PWFA ACCELERATOR PHYSICS

AWAKE





✧Laser ionization of a metal vapor (Rb),
3-4m plasma for p⁺ self-modulation only, SEEDING NECESSARY!

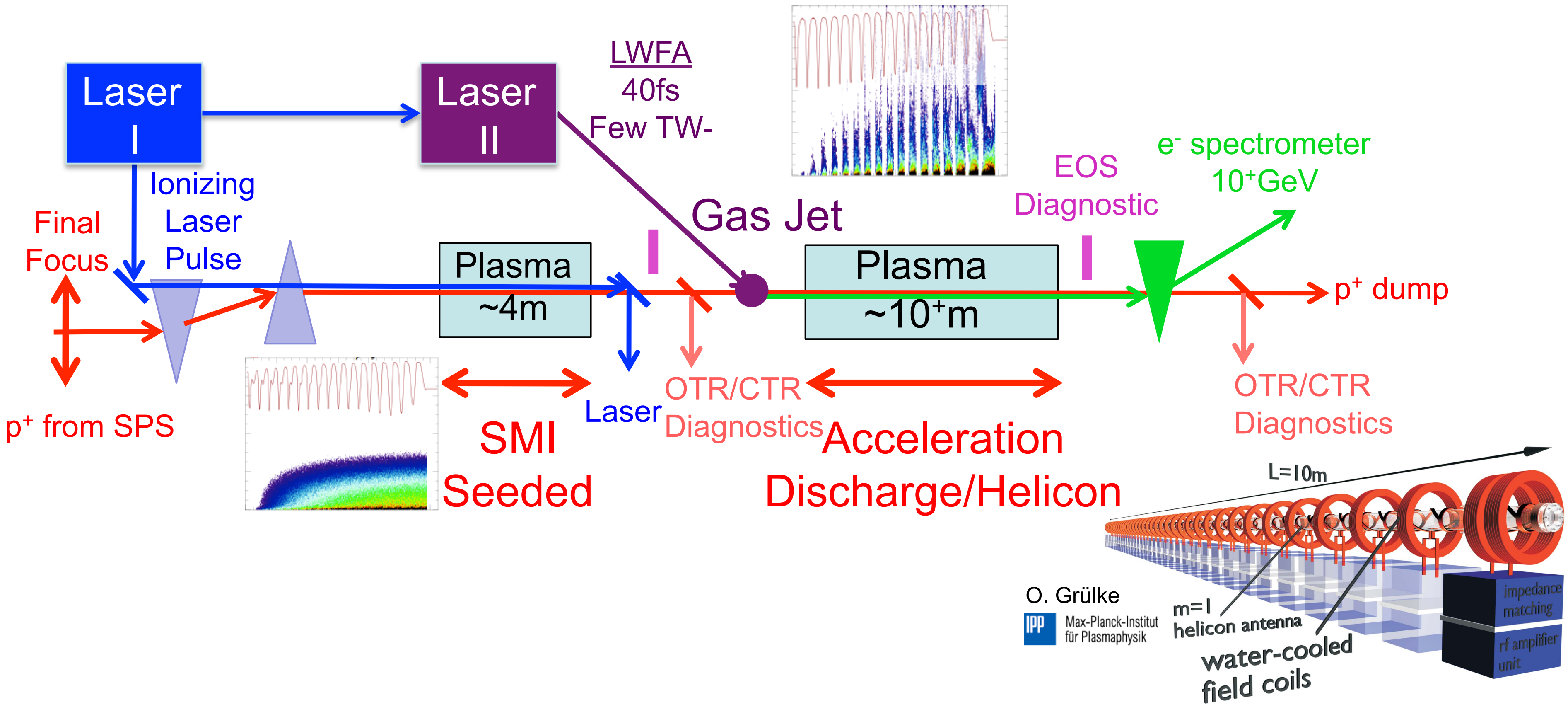
✧~10m discharge or helicon source for acceleration only (scales to 100's m)

✧Inject short e⁻ bunch ($\sigma_z \ll \lambda_{pe}$)

✧Maybe able to tune plasma densities to maintain accelerating gradient

MAX-PLANCK-GESELLSCHAFT

p+-PWFA ACCELERATOR PHYSICS



✧LWFA e^- injector: synchronization, short $\sigma_{ze-} << \lambda_p$, high-current (kA) bunch, beam loading...)

Muggli, IPAC'2014 Proceedings

OUTLINE

- Introduction to Plasma Wakefield Accelerator (PWFA)
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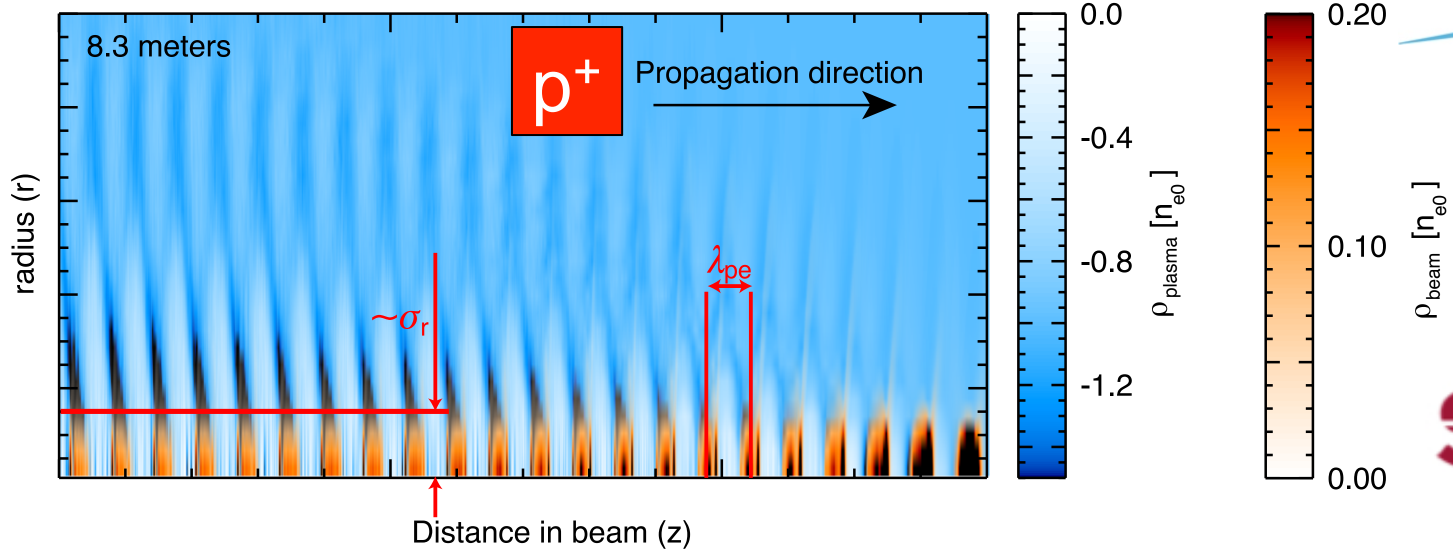
COMPARISON +/- DRIVEN PWFA

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

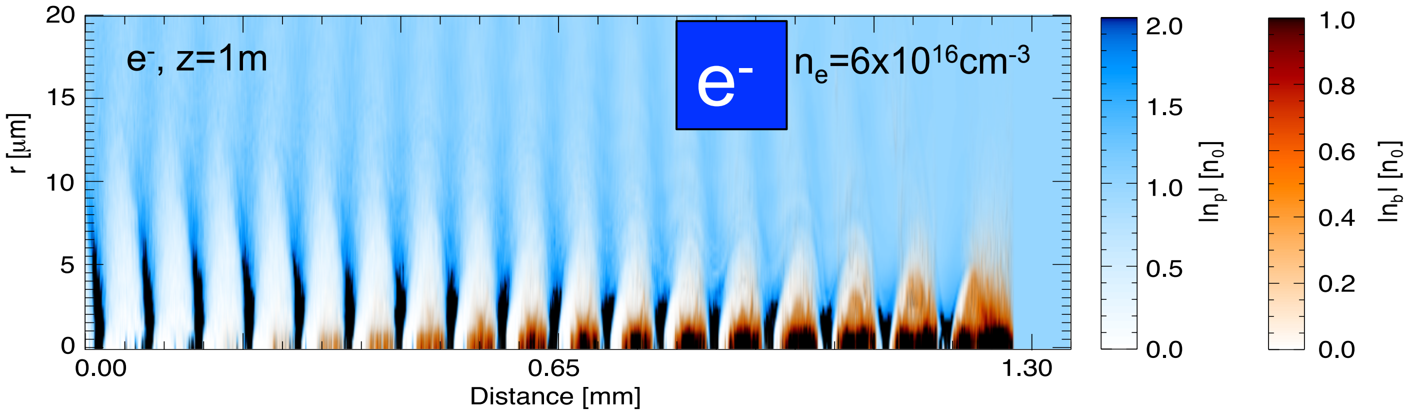
AWAKE

- Comparison positively/negatively charged bunches

AWAKE p^+



SLAC e^+



SLAC e^-

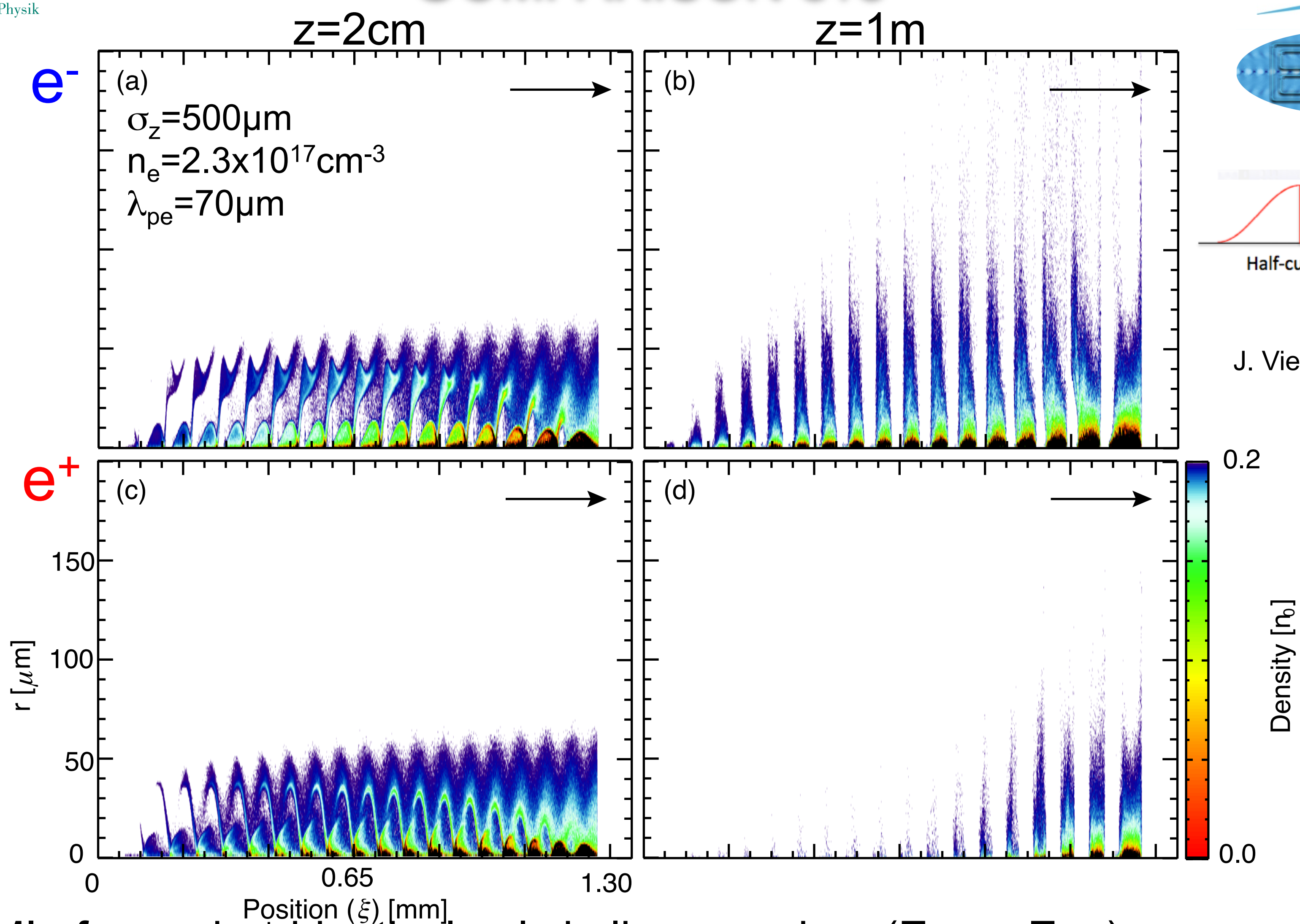
Simulations: J. Vieira

- Phase difference, as expected from simple physics

MAX-PLANCK-GESELLSCHAFT

Vieira, Phys. Plasmas 19, 063105 (2012)

Comparison e^-/e^+



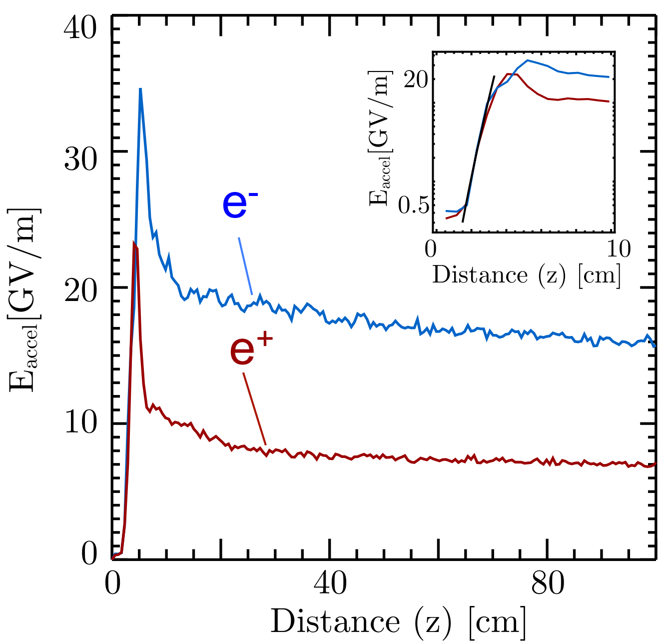
Half-cut e- Bunch

J. Vieira, IST

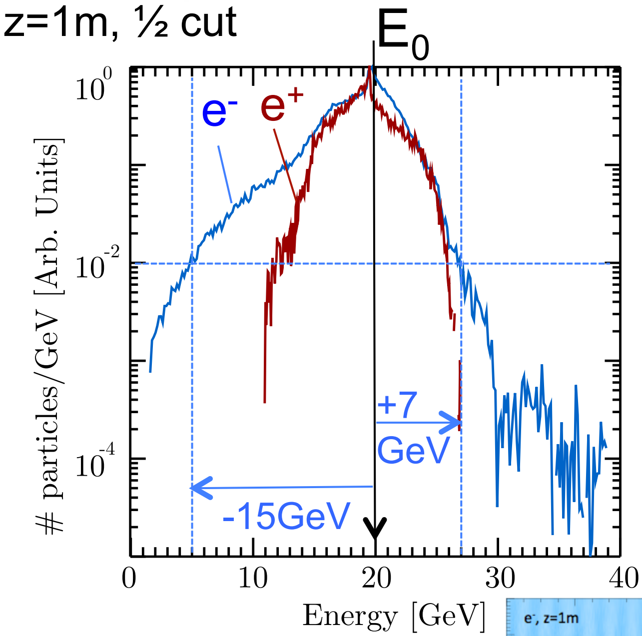
- ✧SMI of e^- and e^+ identical only in linear regime (E_{acc}<<E_{WB})
- ✧SMI leads to the resonant excitation of wakefields
- ✧Less e^+ remain to drive wakefields in the non-linear regime

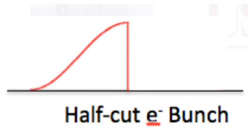
Vieira, Phys. Plasmas 19, 063105 (2012)

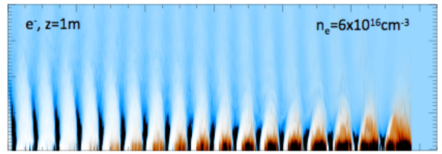
WAKEFIELDS & ENERGY CHANGE
(by drive particles)



z=1m, ½ cut







- ✧Peak SMI wakefield (~35GV/m) ~ single bunch peak field (~50GV/m)
  E_{WB}=46GV/m @ n_e=2.3x$10^{17}$$cm^{-3}$
- ✧Large energy loss >10GeV (e^- @1%/GeV level)
- ✧Energy gain >5GeV (e^-, e^+ @1%/GeV level)
- ✧No externally injected particles

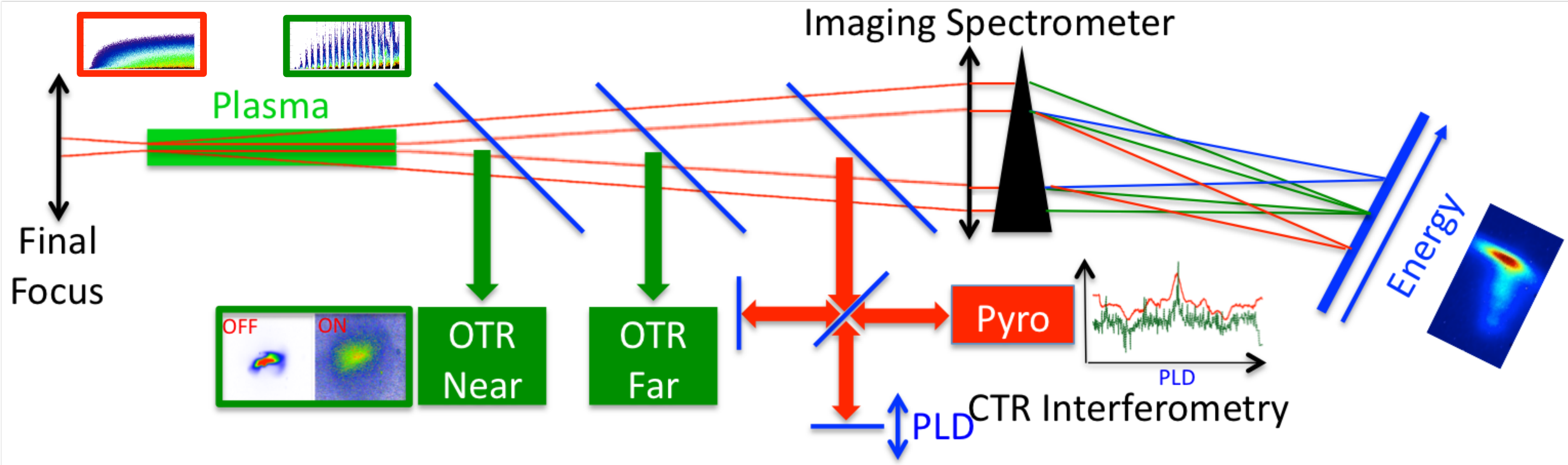
Vieira, Phys. Plasmas 19, 063105 (2012)

E209 @ SLAC

- SMI physics with e^- and e^+
- Seeding SMI with shaped bunch in pre-formed plasma
- SMI – hosing instability competition
- No externally injected e^-
- Multi-GV/m wakefields
- Encouraging initial results after two-day experiment …
- Observed the 3 observables:
  - Energy loss (no gain?)
  - Radial modulation (CTR)
  - Halo formation (OTR)

E209 @ SLAC

The same as E200 and E201



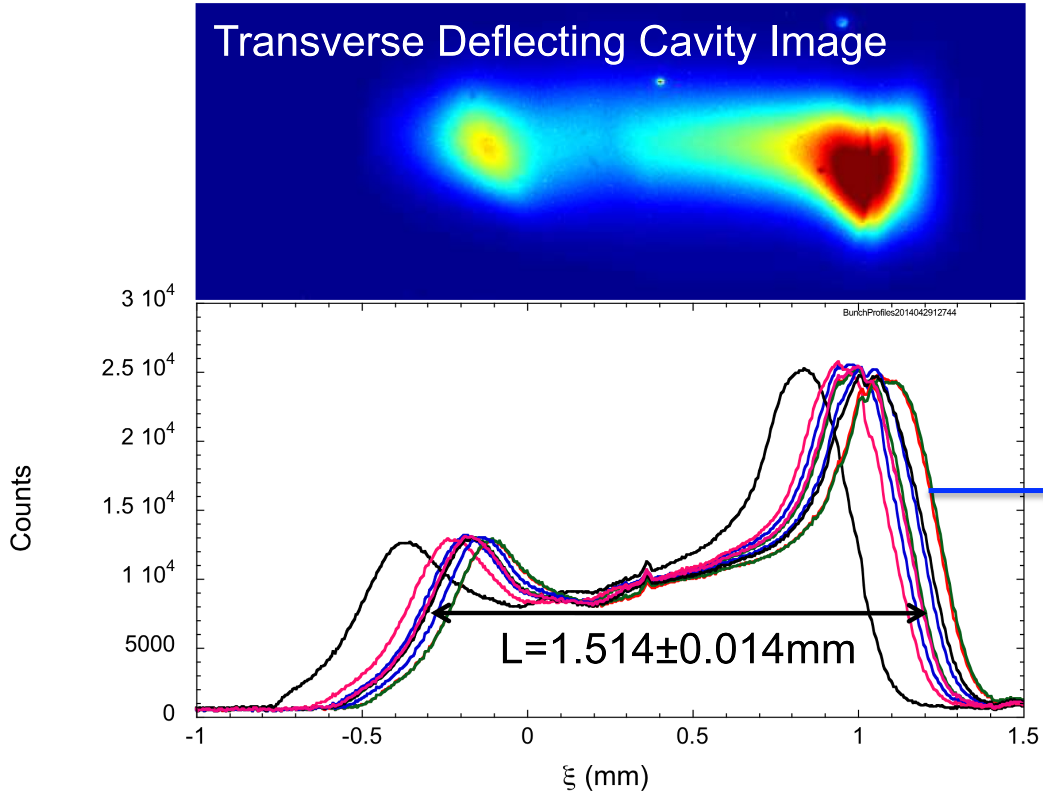
Three observables:

- ✧Energy loss/gain by drive bunch particles
- ✧Formation of transverse halo (defocused particles)
- ✧Radial size modulation (CTR interferometry)

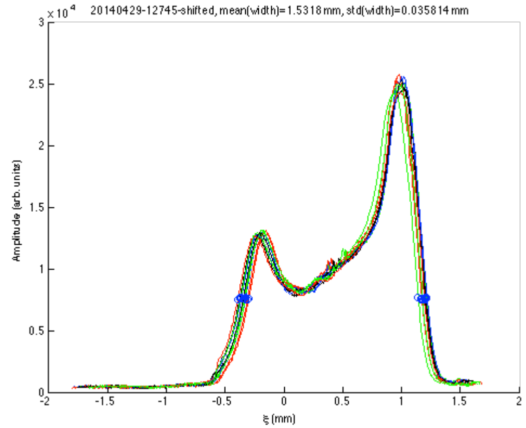
Three well established diagnostics at FACET:

- ✧Magnetic spectrometer with ~100MeV resolution
- ✧Two OTR systems ~1 and ~2m downstream from the plasma
- ✧CTR interferometry ~1.5m downstream from the plasma

BEAM & PLASMA PARAMETERS



Two sets of ten, aligned profiles ….



✧Bunch longitudinal profile very consistent …

✧$L_{\text{blue points}}$=1.514±0.014mm

e^- beam:

E=20.35GeV

N_{e-}=1.9x10^{10}

σ_r~40µm

ξ~1500µm FWHM

L/λ_{pe}~14

n_b/n_e~2%

Plasma (E200):

n_e=8x10^{16}cm^{-3} => λ_{pe}=115µm

L_p~1.3m

✧Discovery: the beam profile is far from Gaussian
(i.e., not as in simulations, so far)

OUTLINE

✧ Introduction to Plasma Wakefield Accelerator (PWFA)

✧ Introduction to the self-modulation instability (SMI)

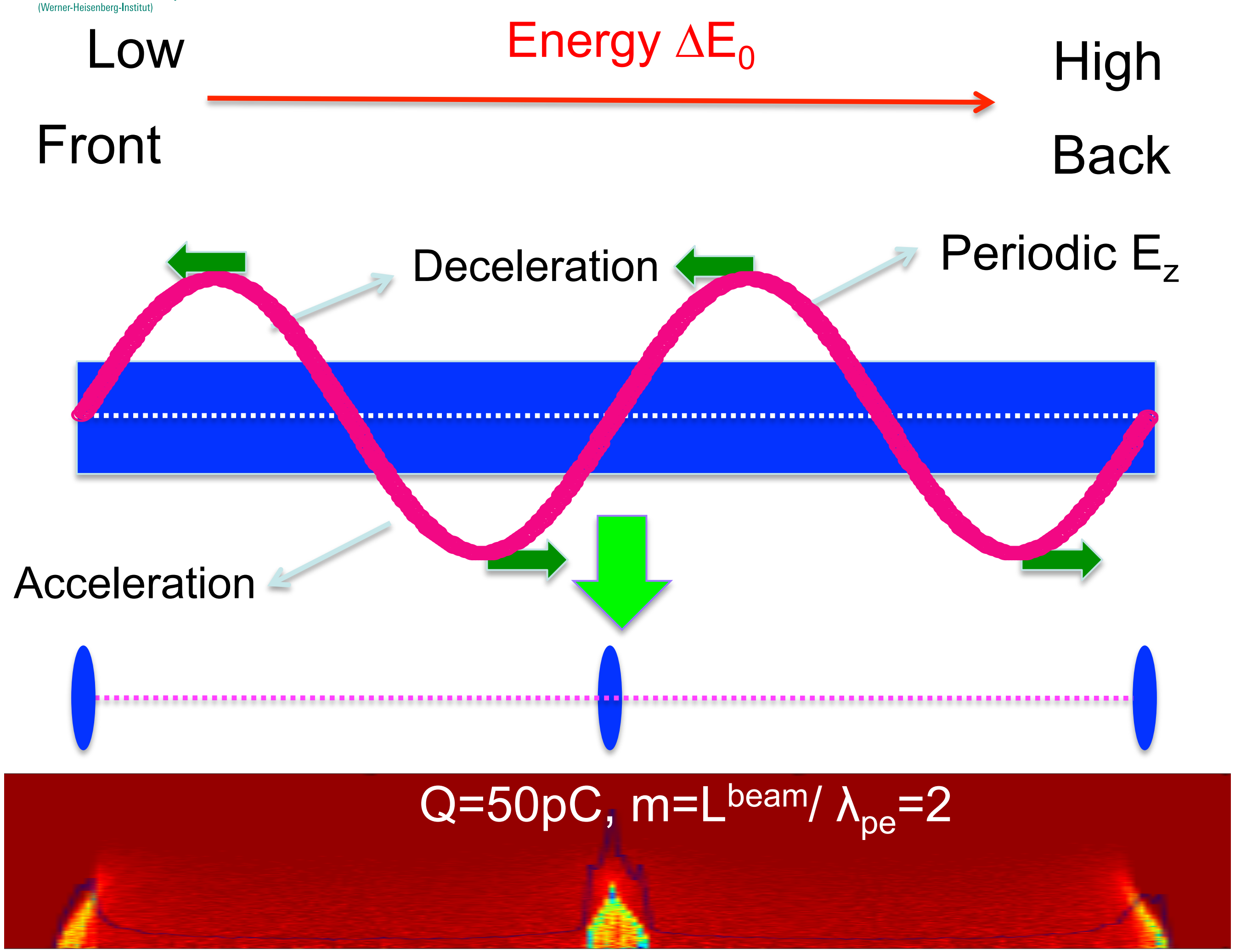
✧ SMI PWFA experiments at CERN with p^+: AWAKE

✧ SMI experiments at SLAC E209 with e^-/e^+

✧ Linear PWFA – SMI seeding at BNL-ATF

✧ Summary

ENERGY SELF-MODULATiON



Energy Gain/Loss:

$$\Delta E = \frac{1}{4}\cdot\frac{\Delta E_0}{m} \qquad m = L^{beam}/\lambda_{pe} = 1,2,..$$

$$E_z = \frac{1}{4}\cdot\frac{\Delta E_0}{m\cdot eL^{plasma}}$$

E_z must decreases from ~6 to ~1.2MV/m to preserve visibility!
Choose Q=50pC

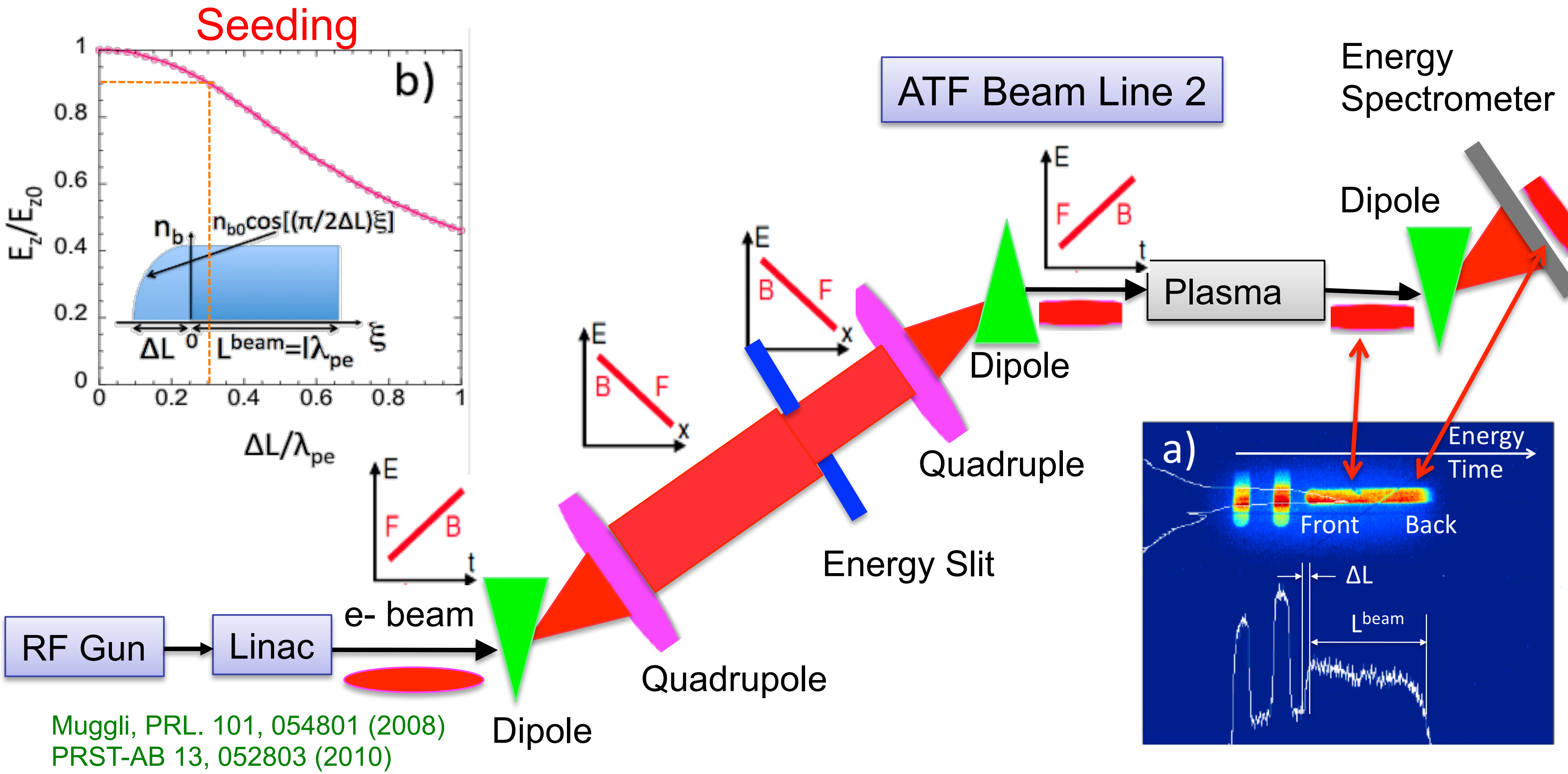
$$E_z(r=0) = \frac{-mQ}{\varepsilon_0 L_b^2 \sigma_r^2}\int_0^\infty e^{-r^2/2\sigma_r^2} K_0(2\pi m/L_b)\, r dr$$

m	$E_{z, opt}$ (MV/m)	$E_{z, lin, OSIRIS}$ (MV/m)	$n_e \sim m^2$ (cm^{-3})
1	5.2	3.7	1.2×10^{15}
2	3.0	3.2	4.8×10^{15}
3	2.0	2.6	1.1×10^{16}
4	1.5	2.1	1.9×10^{16}
5	1.2	1.8	3.0×10^{16}

- Similar to FEL energy modulation / velocity bunching
- Indirect evidence ($W_{//}=E_z$) of driving of wakefields that can seed the SMI: $W_{perp}=(E_r-cB_\theta)\alpha W_{//}$

Work by Y. Fang, USC

EXPERIMENTAL SETUP



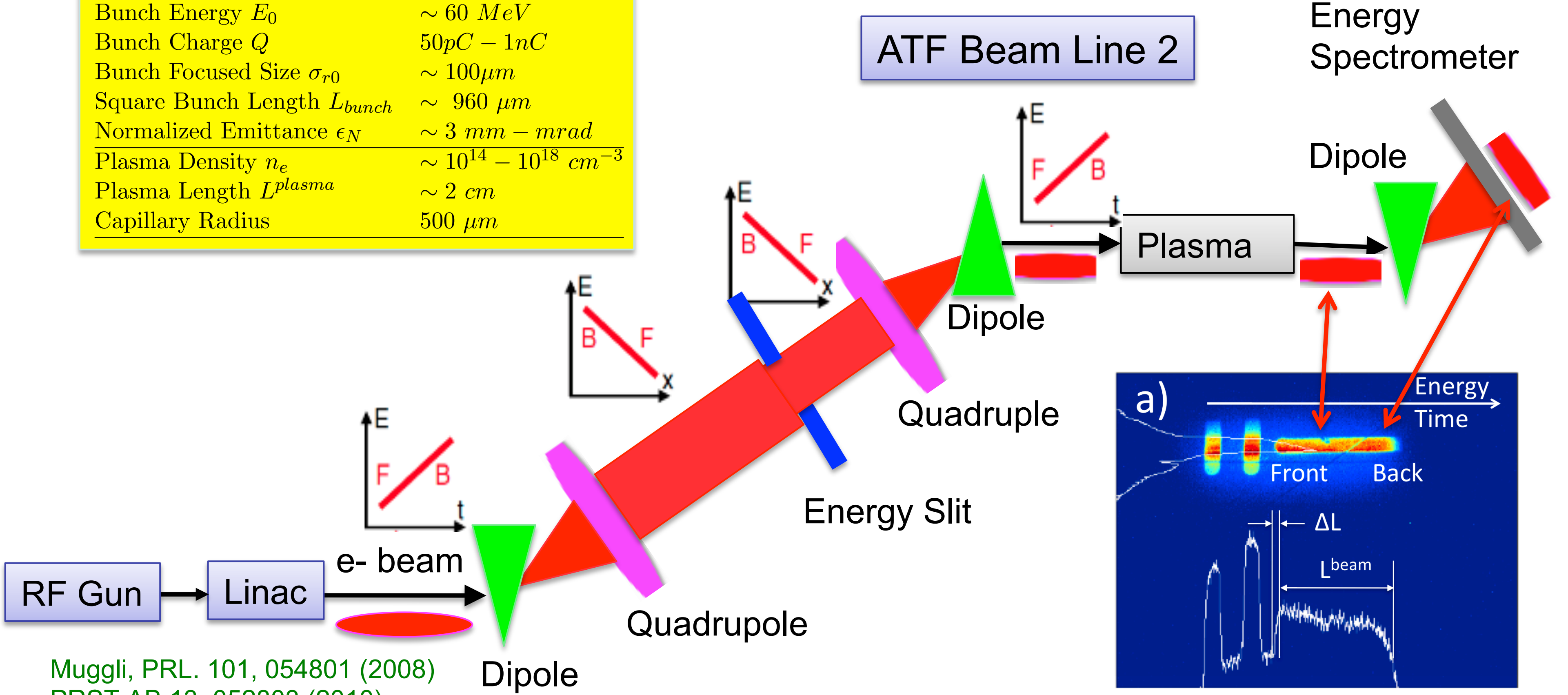
Muggli, PRL. 101, 054801 (2008)
PRST-AB 13, 052803 (2010)

- ✧Use masking method to produce “square” bunch for SMI seeding
- ✧Need cut/step<<λ_{pe}: <0.3λ_{pe} in exp. => E_{z0}>0.9E_{z0} sharp

Work by Y. Fang, USC

EXPERiMENTAL SETUP

Parameter	*Value*
Bunch Energy E_0	$\sim 60\ MeV$
Bunch Charge Q	$50pC - 1nC$
Bunch Focused Size σ_{r0}	$\sim 100\mu m$
Square Bunch Length L_{bunch}	$\sim\ 960\ \mu m$
Normalized Emittance ϵ_N	$\sim 3\ mm - mrad$
Plasma Density n_e	$\sim 10^{14} - 10^{18}\ cm^{-3}$
Plasma Length L^{plasma}	$\sim 2\ cm$
Capillary Radius	$500\ \mu m$



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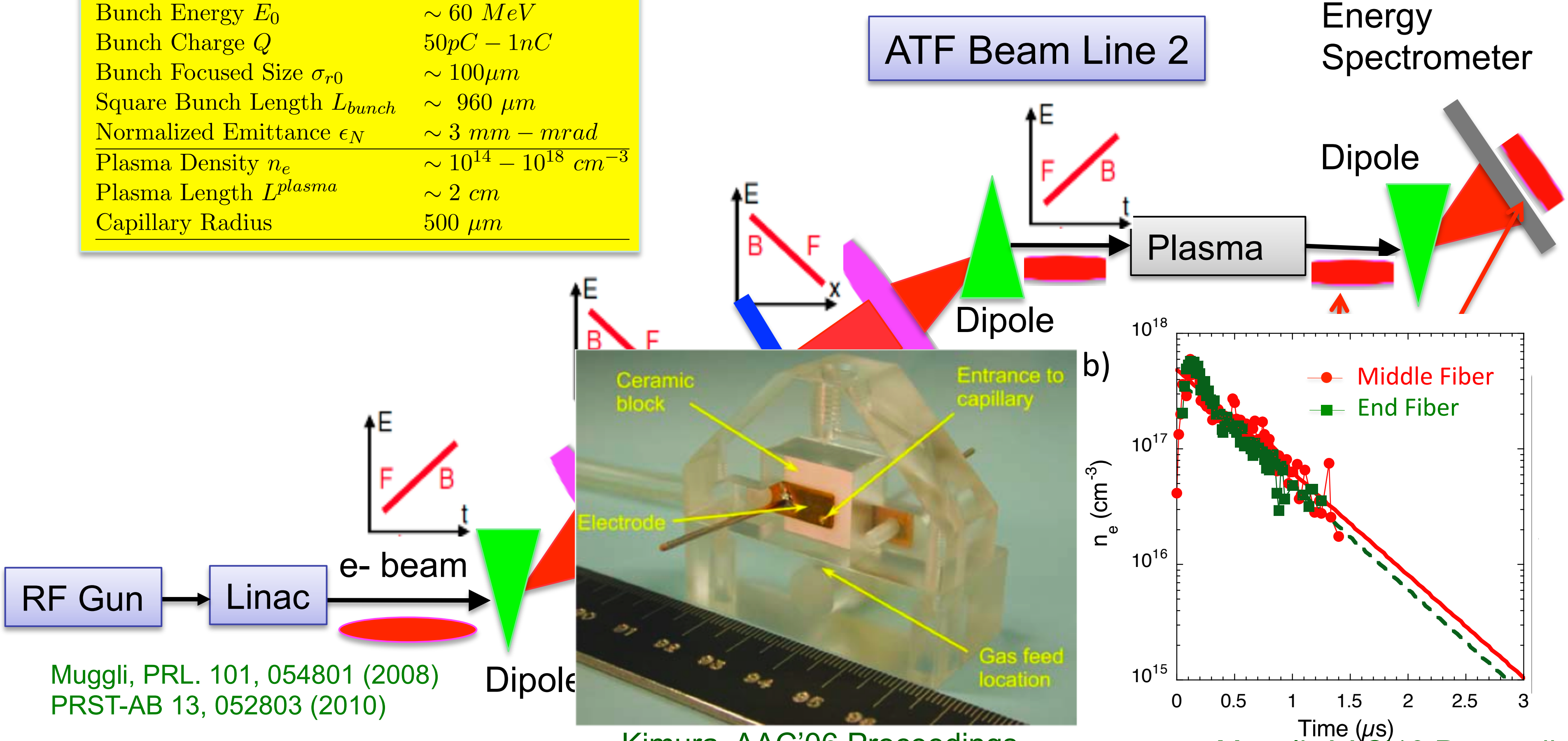


Muggli, PRL. 101, 054801 (2008)
PRST-AB 13, 052803 (2010)

Kimura, AAC'06 Proceedings

Muggli, AAC'10 Proceedings

✧Use masking method to produce "square" bunch for SMI seeding

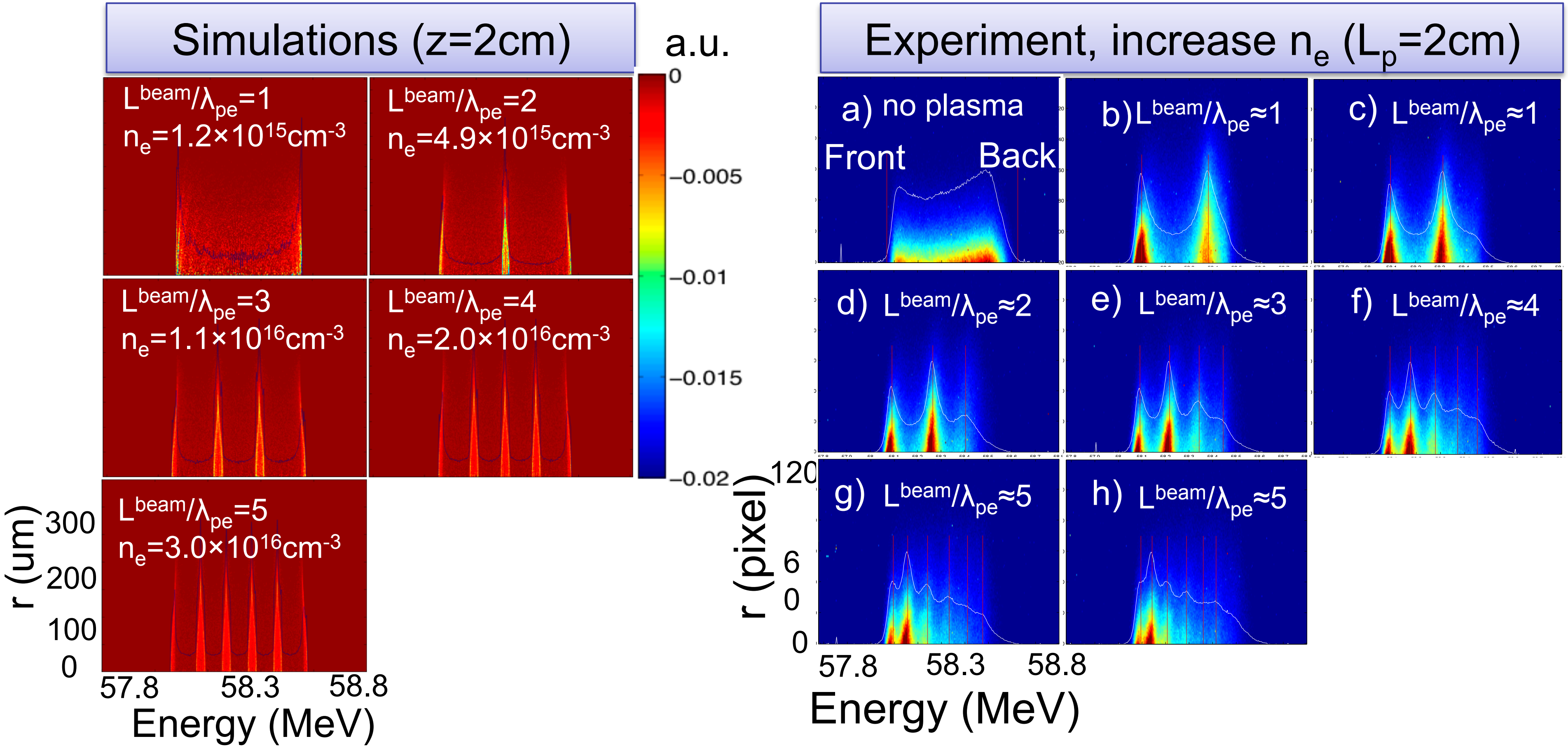
✧Need cut/step<<λ_{pe}: <0.3λ_{pe} in exp. => E_{z0}>0.9$E_{z0\ sharp}$

✧n_e ⇔ discharge – beam delay

Work by Y. Fang, USC

OBSERVATION OF (ENERGY) SELF-MODULATION

✧ATF "square" e^- bunch, Q=50pC, ΔE_0=0.5MeV in 960µm, in 2m plasma, variable n_e



Fang et al., PRL 112, 045001 (2014).

✧Simulations/experiments very similar

✧Visibility in experiment confirms E_z variation with n_e

✧First observation of SMI seed: E_z instead of E_r-cB_θ

OUTLINE

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✧ Summary

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

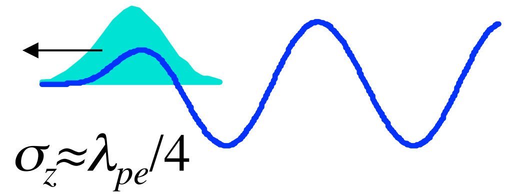
5 ~~4~~ PLASMA ACCELERATORS*

AWAKE

- Plasma Wakefield Accelerator (PWFA)

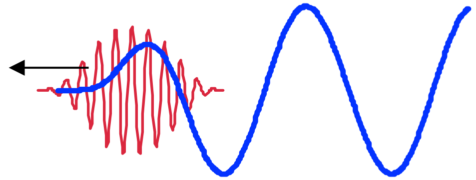
  A high energy particle bunch (e^-, e^+, ...)

  P. Chen et al., Phys. Rev. Lett. 54, 693 (1985)



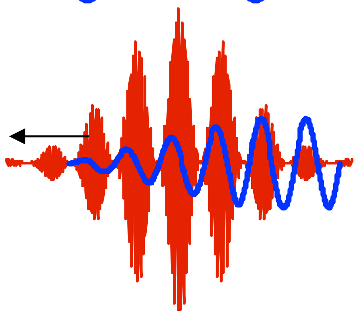
- Laser Wakefield Accelerator (LWFA)

  A short laser pulse (photons)



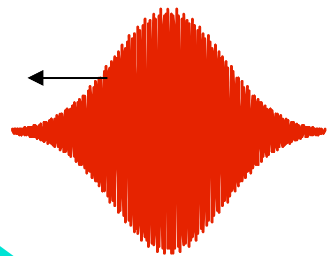
- Plasma Beat Wave Accelerator (PBWA)

  Two frequencies laser pulse, i.e., a train of pulses

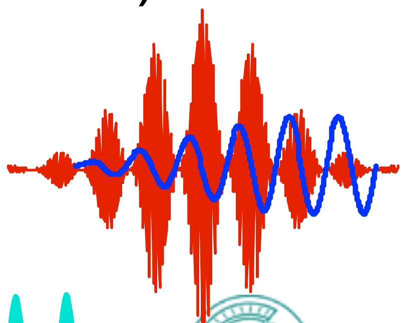


- Self-Modulated Laser Wakefield Accelerator (SMLWFA)

  Raman forward scattering instability
  in a long laser pulse

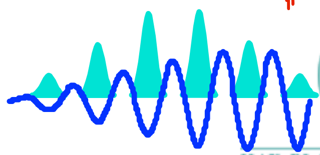


evolves into



- Self-Modulated PWFA (sMPPWFA)

evolves into



*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

SUMMARY

✧ p^+ bunches: only drivers with enough energy for PWFA to the energy frontier

✧Observe self-modulation instability (SMI) of long particle bunches in plasma

✧ SMI PWFA experiments at CERN with p^+ (approved 2013, experiments 2016)

- PWFA driven by p^+ bunch
- SMI of p^+ bunch
- Seeding (laser ionization)
- ~GV/m over 10m
- External injection of electrons
- …
- Beginning of a long term program at CERN for p^+-driven PWFA

✧SLAC E209 SMI physics experiment with e^-/e^+

- Transverse modulation, large wakefields (~10GV/m), seeding (cut bunch), SMI/ hosing competition, e^-/e^+ differences
- Signs of radial modulation, energy loss, halo formation in two-day experiment!!!

✧Signs of SMI seeding in ATF experiments

✧Other SMI experiments (DESY, CLARA-UK, INFN-Frascati, …)

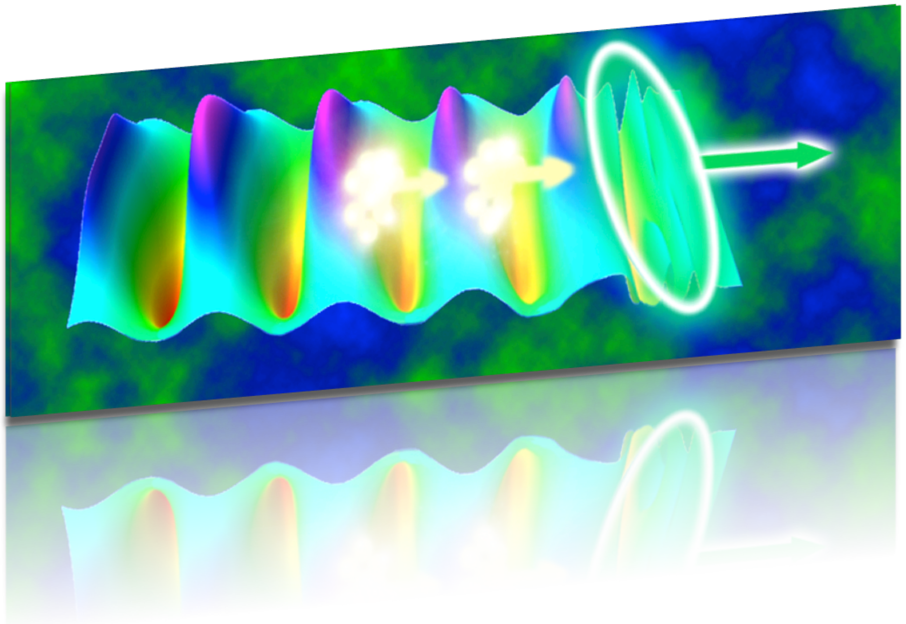
✧Simulations play a key role …

✧AWAKE = open collaboration

Advanced WAKefield Experiment

AWAKE

Proton-driven Plasma Wakefield Accelerator at CERN



- Proof-of-principle experiment: accelerate in a short distance charged particles
- Candidate for future high energy accelerators
- Toward single-stage TeV lepton accelerator

Thank you!

Thank you to my collaborators!

http://www.mpp.mpg.de/~muggli
muggli@mpp.mpg.de